To the Graduate Council:

I am submitting herewith a dissertation written by Lay Choo Lee-Tan entitled "Studies of Organic Reactions on Alumina. I. Macrocyclization with S^{-2}/Al_2O_3. II. Chemical and Physical Characterization of Al_2O_3 and Modified Al_2O_3. III. Diels-Alder Reaction on BX_3/Al_2O_3 and Al_2O_3." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Chemistry.

Richard M. Pagni, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

STUDIES OF ORGANIC REACTIONS ON ALUMINA

I. MACROCYCLIZATION WITH S^{-2}/Al_2O_3

II. CHEMICAL AND PHYSICAL CHARACTERIZATION OF Al_2O_3 AND MODIFIED Al_2O_3

III. DIELS-ALDER REACTION ON BX_3/Al_2O_3 AND Al_2O_3

A Dissertation

Presented for the

Doctor of Philosophy

Degree

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Lay Choo Lee Tan

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I wish to dedicate this dissertation to my husband,

Chin-Teck Tan,

my best friend in the world.

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Finally, Teck, from the bottom of my heart, *Terima Kasih!*

Abstract

The reactions of a series of terminal dibromoalkanes with S^{-2} on Al_2O_3 were examined. The use of γ-alumina as a solid support for the macrocyclization reactions appeared to be a viable procedure to the more traditional high dilution technique in solution. In addition, cyclization reactions were performed with thioacetamide on activated and unactivated aluminas.

Experiments were also carried out to study the characteristics of alumina of various activity and modified aluminas such as BBX_3/Al_2O_3 and CCl_4/Al_2O_3. Alumina was treated with CCl_4 to determine the number of O^{-2} anions on the surface of alumina. Qualitative and quantitative measurements were taken to determine the acidity of these aluminas.

Boron tribromide (BBr_3), a Lewis acid, was adsorbed on alumina and experiments were carried out to study the effect of joint participation of BBr_3/Al_2O_3 on the Diels-Alder reactions.

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LIST OF ABBREVIATIONS

PART I : MACROCYCLIZATION WITH S^{-2}/Al_2O_3

HMPT	Hexamethylphosphoric Triamide
S^{-2}/Al_2O_3	Sulfide on Alumina
CH_3CSNH_2	Thioacetamide
Al_2O_3	Alumina
$Bu_3SnSSnBu_3$	*Bis*(tributyltin)sulfide
F^-/Al_2O_3	Fluoride on Alumina
$Na_2S{\cdot}9H_2O$	Sodium Sulfide Nonahydrate
^1H NMR	Proton Nuclear Magnetic Resonance
GC	Gas Chromatography
GC/MS	Gas Chromatography/Mass Spectrometry
pet. ether	Petroleum Ether
Temp.	Temperature
MHz	Megahertz
lit.	Literature
$CDCl_3$	Deuterated Chloroform
δ	Chemical Shift,Parts per Million
m.p.	Melting Point
m/z	Mass-to-Charge Ratio
cal'd	Calculated

PART II: CHEMICAL AND PHYSICAL CHARACTERIZATION OF Al_2O_3 AND MODIFIED Al_2O_3

CP	Cyclopentadiene
MA	Methyl Acrylate
F^-/Al_2O_3	Fluoride on Alumina
SS NMR	Solid State Nuclear Magnetic Resonance
MAS	Magic Angle Spinning
CP/MAS	Cross Polarization/ Magic Angle Spinning
wt.	Weight
CCl_4	Carbon Tetrachloride
BBr_3	Boron Tribromide
BCl_3	Boron Trichloride
BF_3	Boron Trifluoride
BBr_3/Al_2O_3	Boron Tribromide Treated Alumina
CCl_4/Al_2O_3	Carbon Tetrachloride Treated Alumina
whh	Width at Half Height
H_o	Acidity Function

PART III: DIELS-ALDER REACTION ON BX_3/Al_2O_3 AND Al_2O_3

BBr_3/Al_2O_3 (400°C)	Boron Tribromide Adsorbed on Alumina that had been Activated at 400°C.
BCl_3/Al_2O_3 (200°C)	Boron Trichloride Adsorbed on Alumina that had been Activated at 200°C.
BF_3/Al_2O_3 (400°C)	Boron Trifluoride Adsorbed on Alumina that had been Activated at 400°C.
$SnCl_4/Al_2O_3$ (400°C)	Tin Tetrachloride Adsorbed on Alumina that had been Activated at 400°C.
$TiCl_4/Al_2O_3$ (400°C)	Titanium Tetrachloride Adsorbed on Alumina that had been Activated at 400°C.
MA	Methyl Acrylate.
DMM	Dimethyl Maleate.
DMF	Dimethyl Fumarate.
MAnh	Maleic Anhydride.
ISP	Isoprene.
CP	Cyclopentadiene.
k_{rel}	Relative Rate Constant.
Et_2O	Diethyl Ether.
^{11}B SS NMR	Boron-11 Solid State Nuclear Magnetic Resonance.
CH_2Cl_2	Methylene Chloride.
BX_3	Boron Trihalide.

PART I

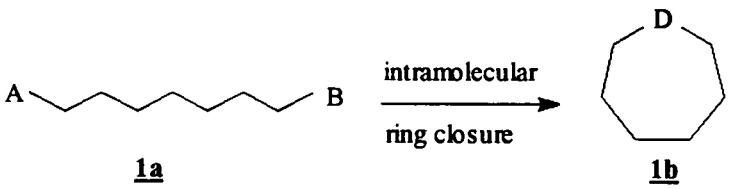
MACROCYCLIZATION WITH S^{-2}/Al_2O_3

CHAPTER 1

INTRODUCTION

The chemistry of molecules with medium and large rings, such as phanes, annulenes and crown compounds has developed rapidly within the last decade. The progress stems from an increased appreciation of the theoretical and practical importance of these compounds, and also by a growing insight into ring closure reactions. The pioneering work of ring closure reactions, particularly in the formation of larger sized rings, was done by Ruzicka[1] and Ziegler.[2] The occurrence of ring compounds in nature and the discovery of the presence of 15- and 17-membered rings in muscone and civetone motivated Ruzicka's interest in macrocyclization reactions.

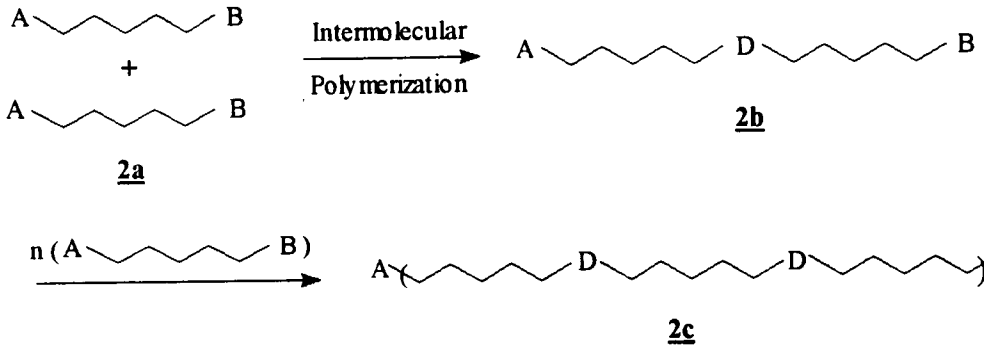
Intramolecular ring closure involves the use of a bifunctional precursor, pictured in equation 1, where A and B are reactive functional groups at the end of a straight chain.[3]



1a **1b** (1)

The ends, A and B, must "meet" in order for ring closure to be successful. The ring formation of medium size rings (8- to 11-membered) is usually difficult because of transannular strain that exists due to repulsive interactions between atoms across the ring

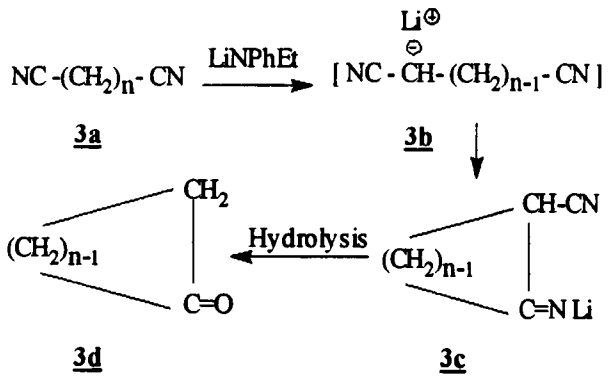
when they are forced close to each other. In addition, these reactions are accompanied by the competition of intermolecular polymerization (eq 2).



(2)

Ruggli[4] and Ziegler[2] developed the high dilution technique in order to favor the intramolecular reaction over the intermolecular reaction. According to Ruggli's high dilution technique, the cyclization reaction is run in a large volume of solvent. This technique is based on the premise that high concentrations of precursor favor polymerization while low concentrations of precursor favor cyclization. On the other hand, Ziegler's high dilution technique involves the very slow introduction of the bifunctional precursor to the solvent in order to minimize the accumulation of the bifunctional precursor in the reaction medium. The technique of Ruggli is simple and is suitable for reactions in which the products cannot withstand prolonged reaction times. His method, however, is seldom used today because of the inconvenience in using large volumes of solvent. For example, as many as 15 liters of solvent have been used to cyclize a few grams of starting material. Ziegler's technique, on the other hand, requires

much less solvent but it is very time-consuming and it often requires special equipment to add the reagents at a slow feed rate.[3a] An example of his work involves the intramolecular Thorpe reaction of dicyanoalkanes[6] (eq 3).



(3)

The results of the intramolecular Thorpe reaction are pictured in Figure I-1.[6] For most reactions, the yield of product is high, but the difficulty in synthesizing 9, 10, and 11 membered rings in high yield still exists.

In 1965, Friedman and Allen attempted to synthesize medium sized cyclic sulfides by reacting sodium sulfide and a series of dibromoalkanes in ethanol.[7] The reaction was performed using the high dilution technique by the slow addition of the dibromoalkane precursor to a solution containing sodium sulfide in ethanol (eq 4).

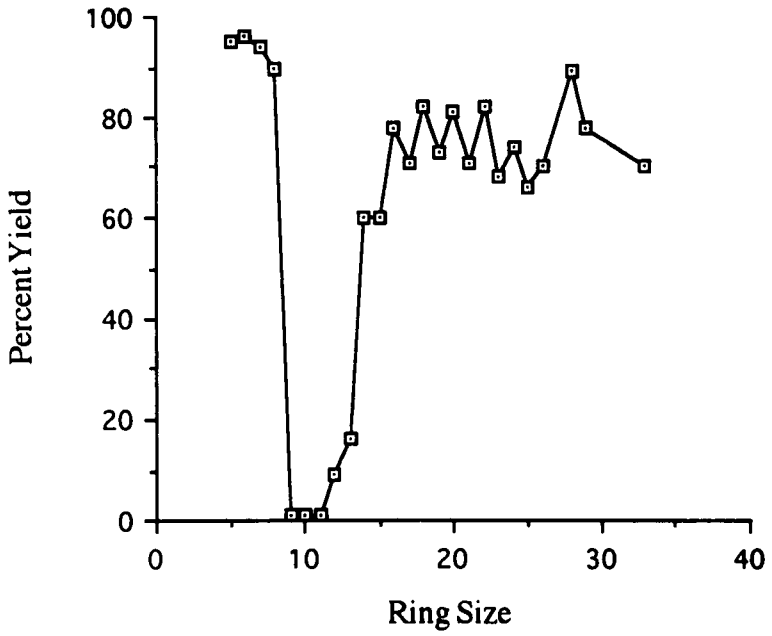
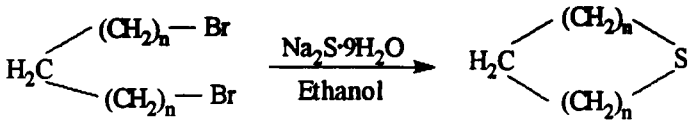


Figure I-1. Percent Yield of Zeigler's Thorpe Reaction of NC-$(CH_2)_n$-CN to Form Cyclic Ketones as a Function of n, where n = 3, 4, 5,...

The reaction procedure involved the simultaneous addition of approximately 0.01 mole of dibromoalkane and 0.02 mole of sodium sulfide, each dissolved in 80 ml of absolute ethanol, to 2.5 liter of refluxing ethanol over a 40 hour period after which the reaction mixture was refluxed for an additional 2 hours. The results of these reactions are summarized in Table I-1. As can be seen, the yields of the cyclic sulfides were still rather low.



4a 4b (4)

where n = 8, 9, 10, 11 and 12

Table I-1. Yields of Cyclic Sulfides by Cyclization of Dibromoalkanes with Sulfide.[7]

Ring Size	% Yield
8	34
9	6.6
10	5.7
11	13
12	3

In 1979, Mandolini *et al.*[8] reported that medium sized cyclic sulfides could be prepared in higher yields if dipolar aprotic solvents were used as the reaction medium in conjuction with the dilution principle method (eq 5). Several dipolar aprotic solvents were used; they were dimethyl formamide (DMF), dimethyl sulfoxide (DMSO) and hexamethylphophorictriamide (HMPT). HMPT turned out give the highest yields of cyclic sulfides (Table I-2).



5a **5b**

(5)

where n = 8, 9, 10, 11, 12, 13, 14 and 15

A typical procedure involved the addition of solutions containing 5.5 mmole of dibromoalkane in 15 ml methanol and an equimolar amount of $Na_2S \cdot 9H_2O$ dissolved in 15 ml methanol to 70 ml of HMPT at 55°C. The addition was carried out over two hours using two dosing syringes.

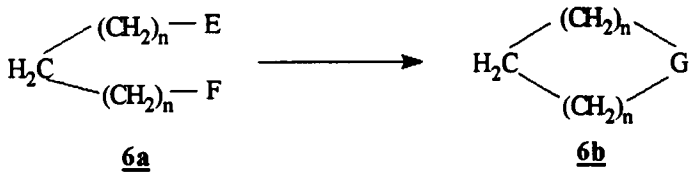
Table I-2. Yields of Cyclic Sulfides by Cyclization of Dibromoalkanes and Sulfide in HMPT.[8]

Ring Size	% Yield
8	78
9	48
10	28
11	22
12	25
13	27
14	55
15	43

CHAPTER 2

GENERAL BACKGROUND

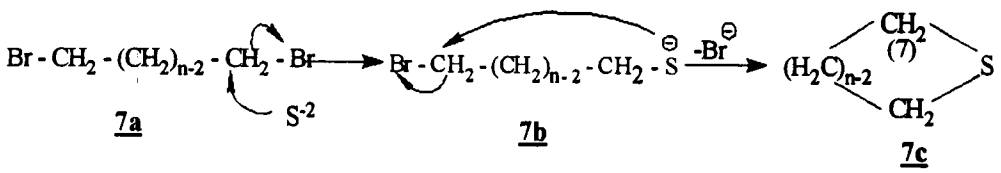
For a cyclization reaction to occur, the reactive functional groups attached to the ends of a chain of methylene groups ($(CH_2)_n$), E and F, must be in close proximity to one another (eq 6).



6a **6b** (6)

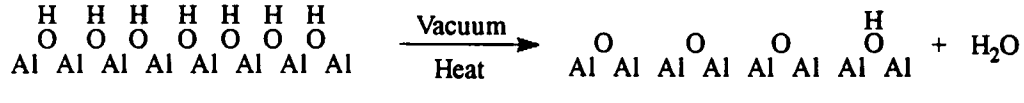
where E and F = reactive functional groups

As the chain length n increases, the probability that the two ends of the chain will be in close proximity decreases. Moreover, because the functional groups, E and F, attached to the ends of the straight chain are free to move, proper orientation of E and F for reaction may not exist even when the groups are in close proximity to one another. If one end of the chain could be inhibited from moving, the probability that the other end of the chain will find it should increase. This should result in a higher yield of cyclized product. For example, in the reaction of a dibromoalkane with sulfide, the S^{-2} end of the intermediate thiolate (**7b**) must attack the bromine containing carbon at the other end of the chain to form the cyclic sulfide (eq 7). If the S^{-1} end of the thiolate in **7b** could somehow be localized, the degrees of freedom of the chain will be reduced. This should result in an increased probability of successful cyclization. One purpose of the research described below was to test this idea.



(7)

Alumina (Al_2O_3) may be a good environment to localize the sulfide nucleophile because of its ability to react with nucleophiles and keep them immobile. According to the theories of Peri[9] and Knözinger and Ratnasamy,[10] alumina has a surface layer of hydroxyl groups that is immediately above a layer of aluminum cations. When the solid is heated under vacuum, adjacent hydroxyl groups react to form water which is driven from the surface (eq 8).

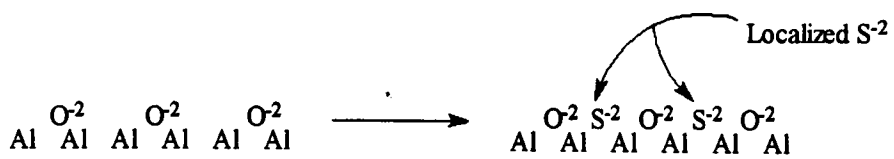


(Unactivated Alumina) (Activated Alumina)

8a **8b**

(8)

The dehydrated alumina has on its surface partially exposed oxide anions (O^{-2} s) and partially exposed aluminum cations (Al^{+3} s). The partially exposed O^{-2} s may function as bases or nucleophiles and the Al^{+3} s as powerful Lewis acids. Furthermore, the partially exposed Al^{+3} cations may react with added nucleophiles such as sulfide to form aluminum-sulfur bonds. These sulfide nucleophiles will thereby become localized on the surface of the dehydrated Al_2O_3 (eq 9). The reactivity of an adsorbed sulfide, of course, ought to be different from its reactivity in the solution.

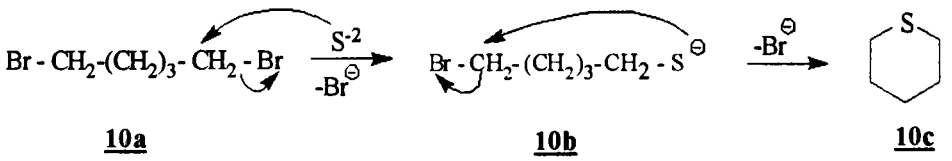


(Dehydrated Alumina) (S^{-2} Adsorbed Alumina)

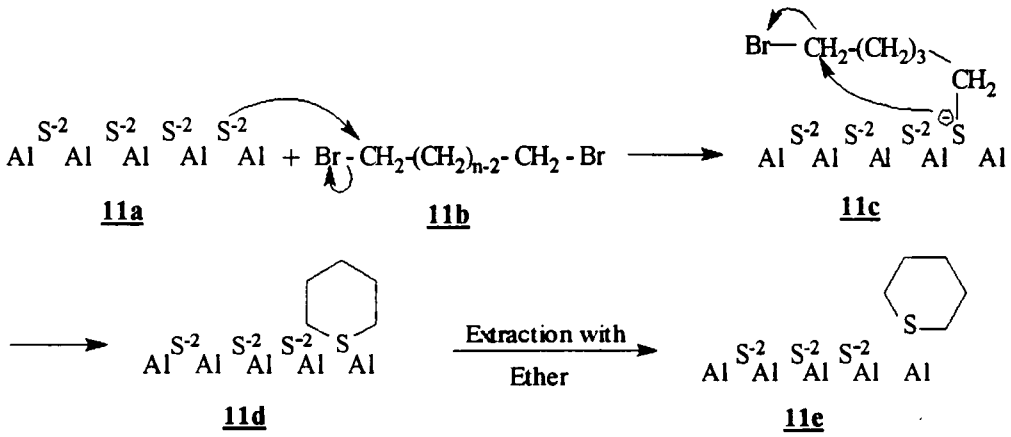
9a **9b**

(9)

Because symmetrical cyclic sulfides have been synthesized in solution by treating sodium sulfide and the appropriate alkyl dihalide with sodium sulfide, it is reasonable to assume these cyclic sulfides can also be synthesized using sulfide that is adsorbed on the surface of dehydrated alumina. The surface analogs of these reactions may prove to have more synthetic utility than their solution counterparts, however. As an example, consider the reaction of 1,5-dibromopentane with Na_2S in solution to form pentamethylene sulfide in two steps from the intermediate thiolate (**10b**) (eq 10). On the other hand, if 1,5-dibromopentane reacts with S^{-2} adsorbed on alumina, the chemistry in equation 11 is expected.



10a **10b** **10c** (10)



11a **11b** **11c**

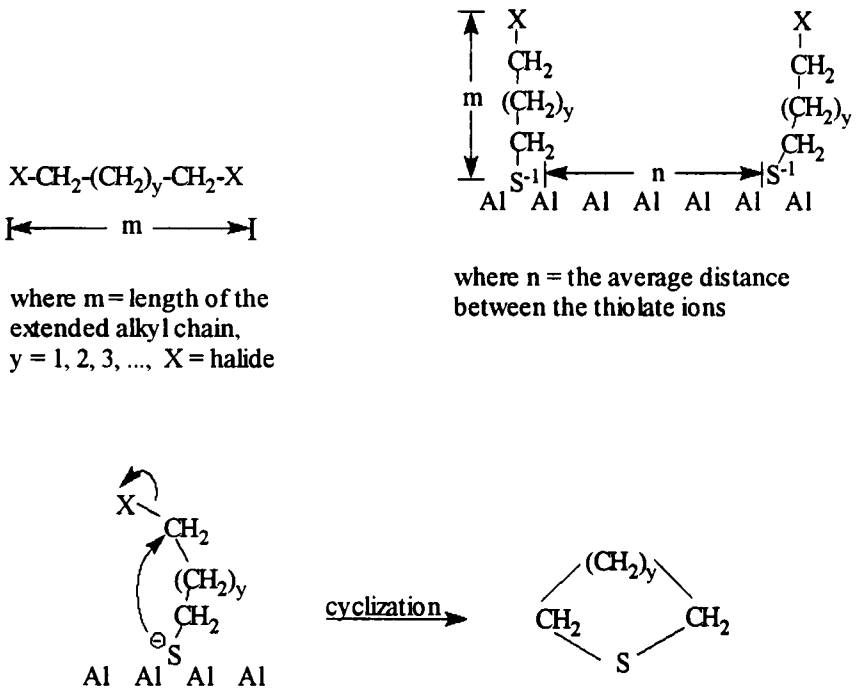
11d **11e** (11)

By localizing the sulfide on the surface of Al_2O_3, the degree of freedom of the straight chain thiolate **11c** should be less than that in thiolate **10b** (eq 10). This should increase the chances of cyclization of the surface attached intermediate.

The focus of this study was to determine if the S^{-2}/Al_2O_3 reagent might be an effective medium for cyclization to occur. We were interested in studying the nucleophilic reactions of S^{-2} on alumina with α,ω-dihaloalkanes to make a series of cyclic sulfide rings with special emphasis on the medium sized and larger rings.

In addition to reducing the degrees of freedom of the chemisorbed intermediate thiolate, there is another reason to believe that S^{-2}/Al_2O_3 might be a superior medium for the cyclization reaction. As mentioned earlier in the INTRODUCTION, intramolecular cyclization in solution is often accompanied by the competition of an intermolecular polymerization. However, if the sulfide and the thiolate are dispersed at sufficiently large distances, only the cyclization will occur. This is pictured in Scheme 1.

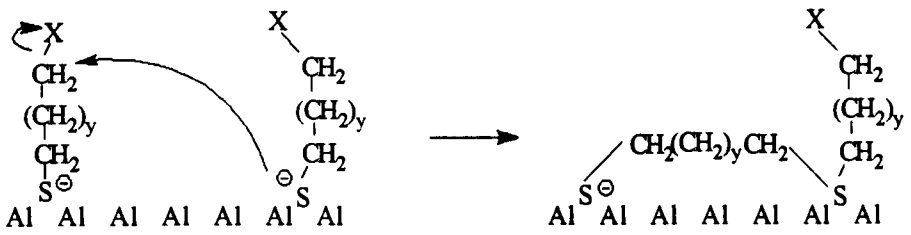
Scheme 1. Cyclization of the Chemisorbed Intermediate Thiolate.



If n > m, cyclization will predominate over intermolecular polymerization

If the amount of S^{-2} impregnated on the alumina is sufficiently low, the average distance between adjacent thiolate ions, n, will be greater than the average length m of the extended alkyl chain (S^{-1}-R-X). If this is so, cyclization will predominate over intermolecular polymerization. If the amount of S^{-2} impregnated on the alumina is high, however, the average distance n between adjacent thiolate ions will be less than the average length of the extended alkyl chain m. Here, intermolecular reactions will compete with the intramolecular cyclization (Scheme 2).

Scheme 2. Intermolecular Reactions of the Chemisorbed Intermediate Thiolates.



where X = halide, y = 1, 2, 3,....

If m > n, intermolecular reactions will compete with the intramolecular cyclization.

Regan *et al.* were the first to impregnate sulfide on neutral alumina using sodium sulfide nonahydrate.[5] Their method consisted of adding neutral alumina to an aqueous solution of sodium sulfide. After removing the excess water *in vacuo* on a rotary evaporator, the resulting free flowing reagent was dehydrated at 110°C under vacuum for 1½ hour.

In one of their studies, primary alkyl halides were treated with sulfide on alumina (S^{-2}/Al_2O_3) to yield the corresponding sulfides (eq 12). The results of these reactions are shown in Table I-3. This is a convenient small scale procedure for the preparation of dialkyl sulfides. The reactions are slow, but the yields of products are reasonably high.

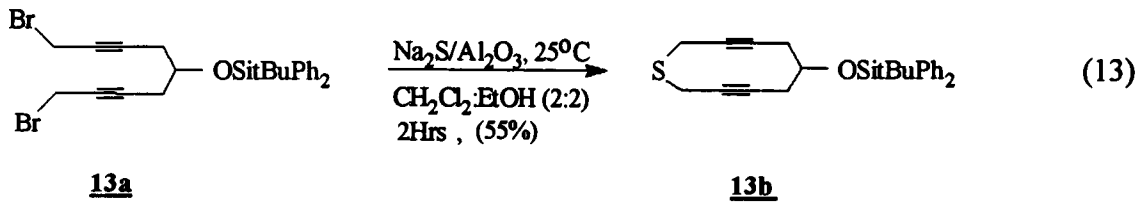
$$\text{R-X} + S^{-2}/Al_2O_3 \longrightarrow \text{R-S-R} \qquad (12)$$

where R = alkyl, X = halide.

Table I-3. Dialkyl Sulfides Prepared by Regen *et al.* using the S^{-2}/Al_2O_3 Complex.[5]

Alkyl Halides R-X	Product	Yield [%]	Reaction Conditions (temperature/time/ solvent)
n-C_4H_9-Br	C_4H_9-S-C_4H_9	98	90°C/20h/toluene
n-C_4H_9-Cl	C_4H_9-S-C_4H_9	89	90°C/20h/toluene
n-C_8H_{17}-Br	C_8H_{17}-S-C_8H_{17}	97	90°C/20h/toluene
n-C_8H_{17}-Cl	C_8H_{17}-S-C_8H_{17}	80	90°C/20h/toluene

In 1989, Nicolaou *et al.*[13] reported the use of S^{-2}/Al_2O_3 in the synthesis of *bis*(propargylic) sulfide **13b**, a new type of DNA cleaving compound (eq 13). Their S^{-2}/Al_2O_3 was prepared by mixing an aqueous solution of Na_2S with Al_2O_3 followed by removal of the water under vacuum at 80°C.



13a **13b** (13)

CHAPTER 3

RESULTS AND DISCUSSION

In our studies, the reactions of alkyl monohalides with the S^{-2}/Al_2O_3 complex were examined first. These and subsequent reactions of alkyl dihalides were performed using a procedure called the slurry method which involves stirring a known amount of alkyl halide or alkyl dihalide with the sulfide/alumina complex in a minimum amount of solvent. An excess of the sulfide/alumina complex was used because some H_2S is lost in the traps of the apparatus used for the preparation of the sulfide/alumina. After the reactions were complete, the products were extracted from the solid, and yields of the products determined by gas chromatography. For all the reactions outlined below, the reaction conditions indicated were those that gave the maximum yield of product(s). Unless stated otherwise, the yields were calculated based on the amount of alkyl halide and alkyl dihalide that had reacted.

Studies were also carried out by reacting a series of dibromoalkanes and the S^{-2}/Al_2O_3 complex. Because product yield in these cases may be inversely related to the concentration of S^{-2} on the alumina, (see INTRODUCTION), the cyclization reactions were run on different loadings of S^{-2} on Al_2O_3. The S^{-2}/Al_2O_3 complexes used in these studies are presented in Table I-4.

Table I-4. The S^{-2}/solid Complexes Used in This Study

mol S^{-2}/g solid Complex[a]	mol S^{-2}/g Al_2O_3[b]	Temp. of Dehydration[c]
6.09×10^{-4}	6.30×10^{-4}	110°C
2.50×10^{-3}	3.10×10^{-3}	110°C
3.33×10^{-3}	4.50×10^{-3}	110°C
4.81×10^{-3}	7.70×10^{-3}	110°C
3.80×10^{-3}	5.40×10^{-3}	110°C
3.66×10^{-3}	5.12×10^{-3}	110°C
5.04×10^{-4}	5.25×10^{-4}	110°C
7.52×10^{-4}	7.99×10^{-4}	110°C
2.42×10^{-3}	2.99×10^{-3}	110°C
2.95×10^{-3}	3.84×10^{-3}	110°C
3.50×10^{-3}	4.81×10^{-3}	110°C
2.92×10^{-3}	3.79×10^{-3}	110°C
4.85×10^{-3}	7.80×10^{-3}	110°C
1.49×10^{-3}	1.69×10^{-3}	95°C
6.02×10^{-4}	6.32×10^{-4}	95°C
2.65×10^{-4}	2.71×10^{-4}	95°C

[a]Mol S^{-2}/g Solid Complex = The number of mols of sulfide/ g of sulfide impregnated alumina.
[b]Mol S^{-2}/g Al_2O_3 = The number of moles of sulfide/ g Al_2O_3 , where the g Al_2O_3 = total weight of sulfide impregnated alumina (solid complex) - weight of Na_2S; see page 16 for calculations.
[c]Method of Dehydration : The S^{-2}/Al_2O_3 complex was dehydrated on the vacuum system designed by Pagni, Kabalka *et al.*[21] The method of dehydration is described in the Experimental Section on page 86.

A. The Preparation of the Sulfide/Alumina Complex

The S^{-2}/Al_2O_3 reagents were prepared in the following manner: A solution of sodium sulfide was dissolved in a minimum amount of distilled water and then stirred with Brockmann Activity 1 neutral alumina for 1 hour. The excess water was removed from the solid by rotory evaporation at 80°C, and the resulting solid activated by heating at either 110°C or 95°C for several hours under vacuum to remove surface hydroxyls on the alumina in the form of water. A sample calculation to determine the number of moles of sulfide adsorbed per gram of alumina and the number of moles of sulfide adsorbed per gram of solid are shown below.

If the reagents consisted of 40.0 g of $Na_2S \cdot 9H_2O$ and 20.0 g of Al_2O_3 (Brockmann Activity 1), then the number of moles of sulfide per gram of alumina in this case is 5.12×10^{-3} mol S^{-2}/g Al_2O_3 and the number of moles of sulfide per gram of solid is 3.66×10^{-3} mol S^{-2}/g solid (solid = sulfide impregnated alumina). These numbers are derived in the following way:

$$40.0\ g\ Na_2S{\cdot}9H_2O \times \frac{1\ mol}{240.18\ g} = 0.166\ mol\ Na_2S{\cdot}9H_2O \equiv 12.9\ g\ Na_2S$$

Total weight of sulfide adsorbed on alumina after dehydration was 45.3 g.

Therefore, the number of moles S^{-2} per gram of alumina is:

$$\frac{0.166\ mol\ Na_2S{\cdot}9H_2O}{32.4\ g\ Al_2O_3} = 5.12 \times 10^{-3}\ mol\ S^{-2}/g\ Al_2O_3$$

where 32.4 g Al_2O_3 = [45.3 g (total weight of solid) - 12.9g (weight of Na_2S)].

The number of moles S^{-2} per gram of solid is:

$$\frac{0.166\ mol\ Na_2S{\cdot}9H_2O}{45.3\ g\ solid} = 3.66\ x\ 10^{-3}\ mol\ S^{-2}/g\ solid$$

Detailed procedures used to prepare the S^{-2}/Al_2O_3 complex are discussed in the EXPERIMENTAL SECTION.

There were distinct color changes upon dehydration of the S^{-2}/Al_2O_3 complex. The color of alumina turned from white to blue-grey upon addition of the aqueous sodium sulfide solution. After the complex was dehydrated under vacuum, the solid was pale green in color at a concentration of 6.09×10^{-4} mol S^{-2}/gram solid and green-peach at a concentration of 2.50×10^{-3} mol S^{-2}/gram solid. Other colors were generated at a higher loading of S^{-2} (Table I-5). The colors are likely due to some type of interaction between the Al_2O_3 and S^{-2}, although the exact nature of this interaction is unknown.

Table I-5. Colors of the S^{-2}/Al_2O_3 Complexes at Various Loadings of S^{-2} on Al_2O_3.

mol S^{-2}/g solid	color upon dehydration
6.09×10^{-4}	pale green
2.50×10^{-3}	green-peach
3.33×10^{-3}	peach
4.81×10^{-3}	peach-orange

It should be noted that sulfide reacts reversibly with water to form hydrogen sulfide and hydroxide anions (eq 14). The newly formed hydrogen sulfide anion, in turn, reacts with another molecule of water to form hydrogen sulfide and another hydroxide anion (eq 15). Removal of the volatile hydrogen sulfide during the preparation of S^{-2}/Al_2O_3 would shift the equilibrium of both reactions to the right.

$$H_2O + S^{-2} \rightleftharpoons HS^- + {}^-OH \quad (14)$$

$$HS^- + H_2O \rightleftharpoons H_2S + {}^-OH \quad (15)$$

These reaction in fact occurred. The water collected in the trap of the vacuum system used to dehydrate the S^{-2}/Al_2O_3 had the distinctive odor of hydrogen sulfide (H_2S). Because H_2S is liberated in the dehydration process, it is difficult to know the exact amount of sulfide ion on the surface of the alumina. In addition, if S^{-2} is not deposited on alumina due to loss of H_2S, ^-OH will be deposited instead. The effect of chemisorbed OH^- on the nature of the S^{-2}/Al_2O_3 complex is not clear.

It is important to store the newly prepared S^{-2}/Al_2O_3 complex under an inert gas. When properly stored in this fashion, the complex gave reproducable results even 21 days after synthesis. However, when the complex was exposed to moisture in the air for more than 1 hour, the complex developed a wet appearance. In addition to giving lower product yield, the moist S^{-2}/Al_2O_3 complex was difficult to stir in the solvents used in the slurry method. It became "gooey" after about 15 minutes of stirring at 80°C and above. This "moisture" problem could be a result of readsorption of water on the surface of the alumina. Exposure of S^{-2}/Al_2O_3 to air may also result in oxidation of sulfide. Because of the loss of S^{-2} as H_2S and the "moisture" problem, the amount of sulfide available on the alumina for reaction is not known exactly. For the present purpose, it was assumed that 100% of the sodium sulfide that was mixed with alumina was impregnated onto its surface in the form of sulfide ions and was available for reaction with an alkyl halide or alkyl dihalide.

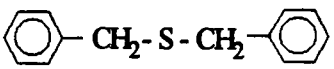
B. The Reaction of Alkyl Monohalides with S^{-2}/Al_2O_3 Complexes.

All the S^{-2}/Al_2O_3 complexes were prepared according to the procedure described on page 19, where the sodium sulfide and alumina mixture were activated at 110°C under vacuum, unless otherwise stated. Initial studies were carried out to optimize the yields of dialkyl sulfides by slurring a series of alkyl halides with the S^{-2}/Al_2O_3 complex. The general reaction sequence was carried out as outlined in equation 16.

$$CH_3(CH_2)_n\text{-}Br + S^{-2}/Al_2O_3 \xrightarrow[\text{Heat or RT}]{\text{Solvent}} [CH_3(CH_2)_n]_2S \qquad (16)$$

A number of dialkyl sulfides, shown in Table I-6, were prepared following this procedure.

Table I-6. Dialkyl Sulfides Prepared by Treating Alkyl Halides with S^{-2}/Al_2O_3 Complexes According to Equation 16.

	$CH_3(CH_2)_7\text{-}S\text{-}(CH_2)_7CH_3$
Dibenzyl sulfide	Dioctyl sulifde
$CH_3(CH_2)_3\text{-}S\text{-}(CH_2)_3CH_3$	$CH_3CH_2\text{-}S\text{-}CH_2CH_3$
Dibutyl sulfide	Diethyl sulfide

The Reaction of Benzyl Chloride with the S^{-2}/Al_2O_3 Complex.

Benzyl chloride was chosen as the first compound for study because of its reactivity in nucleophilic substutition reactions and its availability. It was also chosen because the expected product, dibenzyl sulfide, is easily characterized by ^1H NMR spectroscopy.

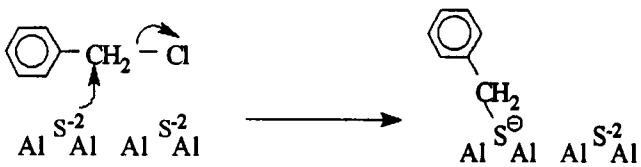
The temperature, time and solvent used to run the reactions between benzyl chloride and S^{-2}/Al_2O_3 were varied as summarized below (Table I-7). In all cases, an excess amount of S^{-2} was used to react with the alkyl halides (RX : mol S^{-2}/g solid ratio used were 1 : $\geq$ 1.2)

Table I-7. Conditions Used for the Reactions of Alkyl Halides with S^{-2}/Al_2O_3 Complexes.

Entry	Condition Used
A.	room temperature for 20 hours in 150 ml of petroleum ether
B.	42°C for 20 hours in 70 ml of petroleum ether
C.	42°C for 20 hours in 150 ml petroleum ether
D.	80°C for 20 hours in 15 ml cyclohexane
E.	80°C for 5 hours in 15 ml cyclohexane
F.	80°C for 3 hours in 15 ml of cyclohexane
G	80°C for 48 hours in 15 ml of cyclohexane

All the reactions were carried out under argon. After slurring the benzyl chloride and the complex under the above reaction conditions, the reaction mixture was then stirred with diethyl ether to extract product and remaining starting material still "bound" to the alumina surface. Dibenzyl sulfide was the only product of the reactions and it was

identified by comparing its ^{1}H NMR and ^{13}C NMR spectra, and the retention time of the gas chromatography (GC), with those properties of an independent dibenzyl sulfide sample. Lack of a good material balance for the reactions can be attributed to benzyl thiolate (**17b**) still chemisorbed to the surface (eq 17). Of the various reaction conditions tried, condition D in Table I-7, gave the best yield (Table I-8). Clearly, longer reaction times and higher reaction temperatures afforded higher yields of product. Interestingly, when the reaction was run at 80°C for 48 hours in cyclohexane, the yield of the product barely increased compared to the reactions run for 24 hours.



(17)

Table I-8. Product Yields for the Various Reaction Conditions Used in the Reaction of Benzyl Chloride and S^{-2}/Al_2O_3 Complex.[a]

Entry	Solvent/(ml)	mol S^{-2}/ g solid	Temp(°C)	Duration	Yield[b]
A	pet ether[c]/150	3.80×10^{-3}	room temp	20 hr	9.6
B	pet. ether/70	3.80×10^{-3}	42	20 hr	12.6
C	pet. ether/150	3.80×10^{-3}	42	20 hr	13.2
D	cyclohexane/15	3.80×10^{-3}	80	20 hr	56.6
E	cyclohexane/15	3.80×10^{-3}	80	5 hr	51.0
F	cyclohexane/15	3.80×10^{-3}	80	3 hr	49.1
G	cyclohexane/15	3.80×10^{-3}	80	48 hr	56.8

[a]The ratio of benzyl chloride to S^{-2} = 1 : 1.4

[b]Yield = Isolated yield of dibenzyl sulfide. Yields (± 1.5) were calculated relative to the amount of alkyl halide that had reacted.

[c]Pet. ether = Petroleum ether.

When benzyl chloride was treated with various loadings of S^{-2} on Al_2O_3 under condition D, the yield of dibenzyl sulfide varied in an interesting manner (Table I-9 and Figure 2 on page 27).

Table I-9. The Effect of S^{-2} Loading on the Yield of Dibenzyl Sulfide from the Reaction of Benzyl Chloride with S^{-2}/Al_2O_3 under Condition D.

Reaction Condition[a]	mol S^{-2}/g solid complex[b]	% isolated yield[c]
D	6.09×10^{-4}	18.0
D	2.50×10^{-3}	42.0
D	3.80×10^{-3}	56.6
D	4.81×10^{-3}	50.0

[a] Condition D: Amount of solvent = 15 ml cyclohexane, Reaction temperature = 80°C, Reaction Duration = 20 hours. [b] The ratio of benzyl chloride to S^{-2} = 1 : 1.4. [c] Yield = Isolated yield (± 1.5) of dibenzyl sulfide; yields were based on the amount of alkyl halide that had reacted.

The 3.80×10^{-3} mol S^{-2}/g solid complex afforded the highest yield of dibenzyl sulfide. Lower or higher concentrations of S^{-2} afforded smaller amounts of dibenzyl sulfide. Nucleophilic substitution of benzyl chloride with sulfide on alumina worked, although the yields of dibenzyl sulfide were not very high. A few other alkyl and aryl halides, benzyl bromide, 1-bromobutane, 1-bromooctane and 1-iodoethane, were studied as well.

Reaction of Benzyl Bromide with the S^{-2}/Al_2O_3 Complex.

Benzyl bromide was likewise treated with the S^{-2}/Al_2O_3 complex under various conditions (Table I-7, page 20), and the results are summarized in Table I-10 and Table I-11. As in the reaction of benzyl chloride with the S^{-2}/Al_2O_3 complex, reaction condition D, with 3.80×10^{-3} mol S^{-2}/g solid, also gave the best results for benzyl

bromide, yielding dibenzyl sulfide in 58.6% yield (GC) (Table I-10). The results for the reaction of benzyl bromide with various loadings of S^{-2} on alumina are summarized in Table I-11 and Figure I-2.

The results shown graphically in Figure I-2 demonstrate that the loading of sulfide on alumina does affect the yield of dibenzyl sulfide from the reaction of benzyl chloride and benzyl bromide in a systematic manner. The yield of benzyl bromide increases as a function of S^{-2} concentration, as expected, reaching a maximum value at 3.80×10^{-3} mol S^{-2}/g solid and then dropping at 4.81×10^{-3} mol S^{-2}/g solid. In the case of 4.81×10^{-3} mol S^{-2}/g solid, where the yield of product has dropped, the adjacent thiolates may be too close to each other, thus inhibiting their subsequent reaction with benzyl halide. At lower S^{-2} concentrations, the thiolates may be sufficiently far apart that this steric inhibition does not operate.

Table I-10. The Effect of Reaction Conditions Used in the Reaction of Benzyl Bromide and the S^{-2}/Al_2O_3 Complex on Product Yield.

Entry[a]	Solvent/(ml)	mol S^{-2}/ g solid[b]	Temp. °C	Duration	Yield[c]
A	pet. ether/150	3.80×10^{-3}	room temp	20 hr	9.9
B	pet. ether/70	3.80×10^{-3}	42	20 hr	14.6
C	pet. ether/150	3.80×10^{-3}	42	20 hr	16.2
D	cyclohexane/15	3.80×10^{-3}	80	20 hr	58.6
E	cyclohexane/15	3.80×10^{-3}	80	5 hr	54.2
F	cyclohexane/15	3.80×10^{-3}	80	3 hr	50.1
G	cyclohexane/15	3.80×10^{-3}	80	48 hr	58.5

[a] See Table I-7 for Reaction Conditions. [b]The ratio of benzyl bromide to S^{-2} = 1 : 1.5. [c]Yield = Isolated yield (± 1.5) of dibenzyl sulfide; yields were based on the amount of alkyl halide that had reacted.

Table I-11. The Effect of S^{-2} Loading on the Yield of Product in the Reaction of Benzyl Bromide with S^{-2}/Al_2O_3 Complexes under Condition D.

Reaction Condition[a]	mol S^{-2}/g solid complex[b]	% isolated yield[c]
D	6.09×10^{-4}	20.4
D	2.50×10^{-3}	40.8
D	3.80×10^{-3}	58.6
D	4.81×10^{-3}	51.2

[a]Condition D: Amount of solvent used = 15 ml cyclohexane, Reaction temperature = 80°C, Reaction duration = 20 hours. [b]The ratio of benzyl bromide to S^{-2} = 1 : 1.5. [c] Yield = Isolated yield (± 1.5) of dibenzyl sulfide.

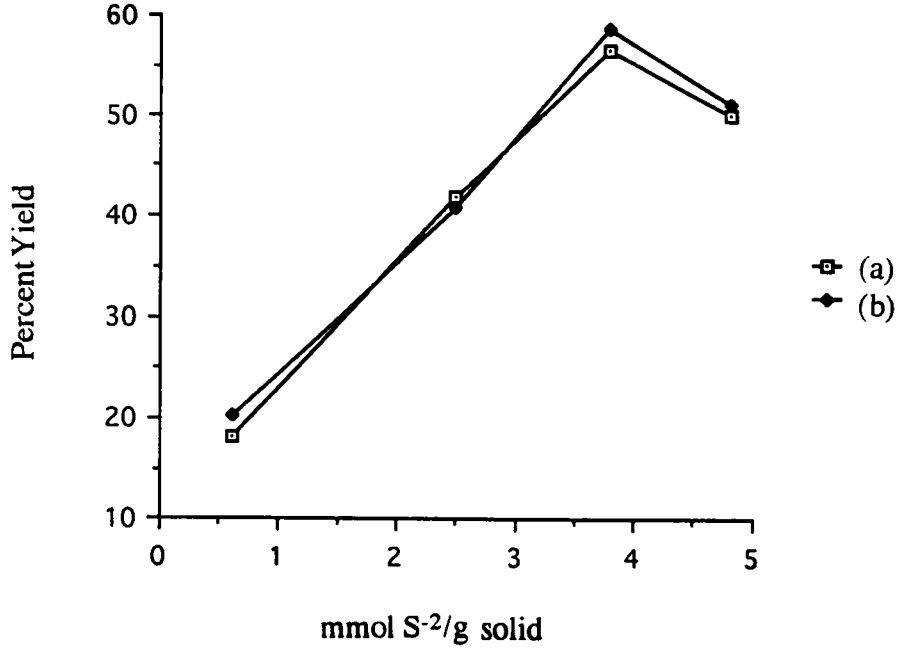


Figure I-2. A Plot of % Isolated Yield of Dibenzyl Sulfide versus the Loadings of S^{-2} on Alumina (mol S^{-2}/g Solid) under Reaction Condition D. (a) Reaction of Benzyl Chloride with S^{-2}/Al_2O_3 Complex. (b) Reaction of Benzyl Bromide with S^{-2}/Al_2O_3 Complex.

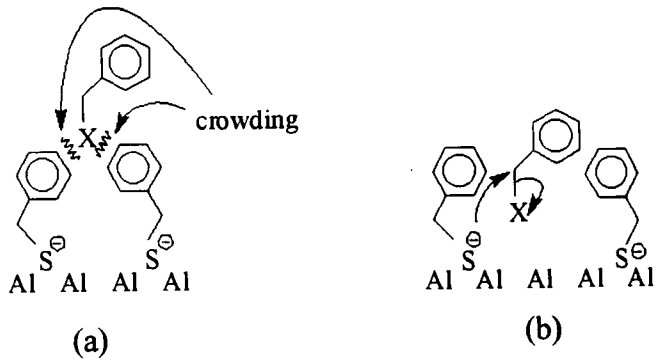


Figure 3. Crowding that Occurs Between Two Adjacent Thiolate Intermediates. (a) At higher S^{-2} concentration, the thiolates may be too close to each other, thus inhibiting their subsequent reaction with benzyl halide. (b) At lower S^{-2} concentration, the thiolates may be sufficiently far apart so that no steric inhibition for subsequent reaction with benzyl halide exists.

Reaction of 1-Bromobutane with S^{-2}/Al_2O_3 Complexes.

1-Bromobutane was treated with S^{-2}/Al_2O_3 complexes under various reaction conditions in an attempt to optimize the yield of di-*n*-butyl sulfide (Table I-12). The best yield of di-*n*-butyl sulfide, 48%, resulted from a reaction run for 24 hours at 80°C in 15 ml of cyclohexane as the solvent, using the 6.09×10^{-4} mol S^{-2}/g solid complex (Table I-12). Stirring with less than 15 ml of solvent resulted in uneven mixing of the reactants, and solvent evaporation under the argon flow was also a problem. It should be noted that longer reaction times and higher reaction temperatures afforded a higher yield of product. However, when the reaction was run at 80°C for 48 hours in cyclohexane, the yield of the product was no higher than for the reaction run for 24 hours. The ^1H NMR spectrum of the isolated product was identical with the spectrum of di-*n*-butyl sulfide in the Sadtler Index Reference.[20] The product was confirmed as di-*n*-butyl sulfide by comparing its retention time and MS (obtained on the GC/MS) with the GC retention time and MS of an independent di-*n*-butyl sulfide sample.

The yields of dibutyl sulfide from the reaction of 1-bromobutane and S^{-2}/Al_2O_3 complex with various sulfide loadings are shown in Table I-13.

Table I-12. The Effect of Reaction Conditions on the Yield of Bu_2S in the Reaction of 1-Bromobutane and the S^{-2}/Al_2O_3 Complex.

Entry[a]	Solvent/(ml)	mol S^{-2}/ g solid[b]	Temp. °C	Duration	Yield[c]
A	pet. ether/150	6.09×10^{-4}	room temp	20 hr	6.4
B	pet. ether/70	6.09×10^{-4}	42	20 hr	10.3
C	pet. ether/150	6.09×10^{-4}	42	20 hr	11.8
D	cyclohexane/15	6.09×10^{-4}	80	20 hr	48.0
G	cyclohexane/15	6.09×10^{-4}	80	48 hr	48.0
E	cyclohexane/15	6.09×10^{-4}	80	5 hr	30.1
F	cyclohexane/15	6.09×10^{-4}	80	3 hr	27.3

[a]See Table I-7 for Reaction Conditions. [b]The ratio of 1-bromobutane : S^{-2} = 1 : 1. [c]Yield = Isolated yield (± 1.5) of dibutyl sulfide; yields were based on the amount of alkyl halide that had reacted.

Table I-13. The Effect of Sulfide Concentration on the Yield of Bu_2S in the Reaction of 1-Bromobutane and the S^{-2}/Al_2O_3 Complex.

Reaction Condition[a]	mol S^{-2}/g solid complex[b]	% isolated yield[c]
D	6.09×10^{-4}	48.0
D	2.50×10^{-3}	40.8
D	3.80×10^{-3}	39.1
D	4.81×10^{-3}	34.3

[a]Condition D: Amount of solvent = 15 ml cyclohexane, Reaction temperature = 80°C, Reaction duration = 20 hours. [b]The ratio of 1-bromobutane : S^{-2} = 1 : 1. [c]Yield = Isolated yield (± 1.5) of dibutyl sulfide; yields were based on the amount of alkyl halide that had reacted.

Reaction of 1-Bromooctane with S^{-2}/Al_2O_3 Complexes.

1-Bromooctane was also treated with S^{-2}/Al_2O_3 complexes using various reaction conditions and loadings of S^{-2} on alumina. Conditions B, C, D, F and G (Table I-7, page 20) were used for these reactions. A single product, a colorless liquid, was isolated from these reactions and identified as di-*n*-octyl sulfide by comparison of its ^1H NMR spectrum with that of the spectrum of di-*n*-octyl sulfide in the Sadtler Index Reference[20] and its GC retention time and MS with the retention time and MS of an independent di-*n*-octyl sulfide sample. Condition D gave an optimum isolated yield of 43.0% of dioctyl sulfide, calculated relative to recovered unreacted starting material (Table I-14).

Table I-14. The Effect of Reaction Conditions on the Yield of Dioctyl Sulfide in the Reaction of 1-Bromooctane and S^{-2}/Al_2O_3.

Entry	Solvent/(ml)	mol S^{-2}/ g solid[a]	Temp. °C	Duration	Yield[b]
B	pet. ether/70	3.80×10^{-3}	42	20 hr	26.3
C	pet. ether/150	3.80×10^{-3}	42	20 hr	22.4
D	cyclohexane/15	3.80×10^{-3}	80	20 hr	43.0
G	cyclohexane/15	3.80×10^{-3}	80	48 hr	43.0
F	cyclohexane/15	3.80×10^{-3}	80	3 hr	28.1

[a]The ratio of 1-bromooctane to S^{-2} = 1 : 1.5. [b]Yield = Isolated yield (± 1.5) of Dioctyl Sulfide.

1-Bromooctane was also treated with varying concentrations of S^{-2} on Al_2O_3 and the results are summarized in Table I-15. A loading of 3.80×10^{-3} mol S^{-2}/g solid gave the highest yield of product. As was observed for benzyl chloride and bromide, the yield

of product went up as the S^{-2} concentration went up, but reached a maximum value and then dropped.

Table I-15. The Effect fo S^{-2} Loading on the Yield of Dioctyl Sulfide for the Reaction of 1-Bromooctane with S^{-2}/Al_2O_3 under Condition D.

Reaction Condition[a]	mol S^{-2}/g Al_2O_3 complex[b]	% isolated yield[c]
D	6.09×10^{-4}	38.1
D	2.50×10^{-3}	40.2
D	3.80×10^{-3}	43.2
D	4.81×10^{-3}	38.2

[a]Condition D: Amount of solvent = 15 ml cyclohexane, Reaction temperature = 80°C, Reaction duration = 20 hours. [b]The ratio of 1-bromooctane to S^{-2} = 1 : 1.5. [c]Yield = Isolated yield (± 1.5) of dioctyl sulfide.

Reaction of 1-Iodoethane with the S^{-2}/Al_2O_3 Complex.

1-Iodoethane was also chosen for study. It was treated with S^{-2}/Al_2O_3 under the previously described reaction conditions, with the goal of finding the conditions that resulted in the best yield of diethyl sulfide. The product was isolated by preparative gas chromatography and had an ^1H NMR spectrum, mass spectrum and GC retention time identical to that of a known sample of Et_2S. The complex that gave the highest yield was 4.81×10^{-3} mol S^{-2}/g solid, using reaction condition D (Table I-7, page 20).

The effect of S^{-2} loading on the reaction of 1-iodoethane and S^{-2} on Al_2O_3 was also examined. The results of these experiments are shown in Table I-17. Clearly here, the yield of product is proportional to S^{-2} concentration.

Table I-16. The Effect of Reaction Conditions on the Yield of Et_2S in the Reaction of 1-Iodoethane and S^{-2}/Al_2O_3.

Entry	Solvent/(ml)	mol S^{-2}/ g solid[a]	Temp. °C	Duration	Yield[b]
B	pet. ether/70	4.81×10^{-3}	42	20 hr	18.2
C	pet. ether/150	4.81×10^{-3}	42	20 hr	14.8
D	cyclohexane/15	4.81×10^{-3}	80	20 hr	21.0
G	cyclohexane/15	4.81×10^{-3}	80	48 hr	21.0
F	cyclohexane/15	4.81×10^{-3}	80	3 hr	16.8

[a]The ratio of 1-iodoethane to S^{-2} = 1 : 1.2. [b]Yield = Isolated yield (± 1.5) of diethyl sulfide.

Table I-17. The Effect of S^{-2} Loading on the Yield of Et_2S for the Reaction of 1-Iodoethane with S^{-2}/Al_2O_3 under Condition D.

Reaction Condition[a]	mol S^{-2}/g solid complex[b]	% isolated yield[c]
D	6.09×10^{-4}	13.4
D	2.50×10^{-3}	18.6
D	3.80×10^{-3}	20.2
D	4.81×10^{-3}	21.0

[a]Condition D: Amount of solvent = 15 ml cyclohexane, Reaction temperature = 80°C, Reaction duration = 20 hours. [b]The ratio of 1-iodoethane to S^{-2} = 1 : 1.2. [c]Yield = Isolated yield (± 1.5) of diethyl sulfide.

The optimum results for the reactions of the five alkyl monohalides with S^{-2}/Al_2O_3 are reported in Table I-18. These data show that, except for 1-iodoethane, all alkyl halides gave moderately good yields of dialkyl sulfide. The behavior of 1-iodoethane is perplexing because it should react faster than the other alkyl monohalides since it has a better leaving group but this is not observed. Perhaps product is lost because of the greater volatility of diethyl sulfide.

Table I-18. Quantitative Data for the Reaction of Alkyl Monohalides with the S^{-2}/Al_2O_3 Complex (Optimum Conditions).

Alkyl Monhalides (amount used)	mol S^{-2}/g Al_2O_3 (amount used)	Reaction Conditions (temp/duration/solv)	% Isolated Yield[a]
Benzyl Chloride	3.80×10^{-3}	80°/20hr/cyclohexane	56.6%
Benzyl Bromide	3.80×10^{-3}	80°/20hr/cyclohexane	58.6%
1-Bromobutane	6.09×10^{-4}	80°/20hr/cyclohexane	48.0%
1-Bromooctane	3.80×10^{-3}	80°/20hr/cyclohexane	43.2%
1-Iodoethane	4.81×10^{-3}	80°/20hr/cyclohexane	21.0%

[a]Yield = Isolated yield (± 1.5) of the corresponding dialkyl sulfide.

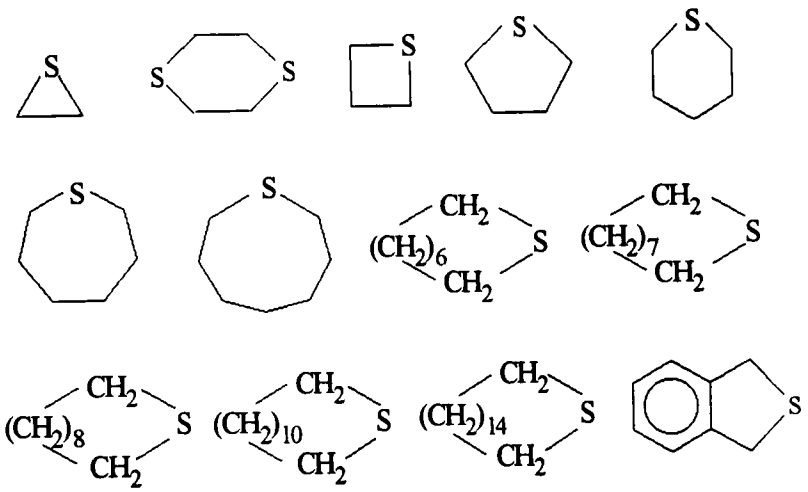
C. The Reaction of Alkyl Dihalides with S^{-2}/Al_2O_3 Complexes.

Because the reactions of alkyl monohalides with S^{-2}/Al_2O_3 by the slurry method were moderately successful, the reactions of alkyl dihalides with the S^{-2}/Al_2O_3 complex were also attempted. The desired reaction sequence for a series of dibromoalkanes with S^{-2}/Al_2O_3 is outlined in equation 18.

$$Br\text{-}(CH_2)_n\text{-}Br + S^{-2}/Al_2O_3 \longrightarrow \underset{\text{where n = 2, 3, 4, 5, 6, 7, 8, 9, 10, 12 or 16}}{\text{cyclic sulfide}} + \text{unreacted starting material} \qquad (18)$$

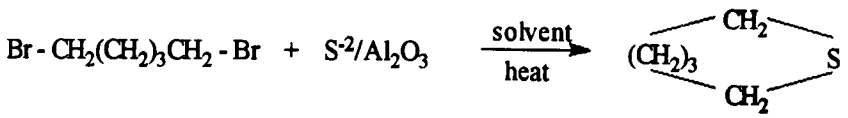
The cyclic sulfides (and a disulfide) prepared by slurrying the dibromides with S^{-2}/Al_2O_3 are presented in Table I-19.

Table I-19. Cyclic Organosulfides Synthesized According to Equation 18.



The Reaction of 1,5-Dibromopentane with the S^{-2}/Al_2O_3 Complex.

1,5-Dibromopentane and S^{-2}/Al_2O_3 (2.42×10^{-3} mol S^{-2}/g solid) complex were reacted under the conditions described in Table I-20, equation 19. The S^{-2}/Al_2O_3 complexes were prepared by activating at 110°C. The goal, as always, was to determine the conditions that would optimize the yield of pentamethylene sulfide. The results of these experiments are shown in Table I-20.



(19)

Table I-20. The Effect of Reaction Conditions on the Cyclization Reaction of 1,5-Dibromopentane with 2.42 x 10^{-3} mol S^{-2}/g solid (110°C)[a]

Condition	Reaction Temperature(°C)	Reaction Time (hours)	Solvent (Volume)	% Yield[b]
H	95°	1	toluene (10 ml)	40.1
I	95°	5	toluene (10 ml)	59.5
J	95°	10	toluene (10 ml)	63.8
K	95°	20	toluene (10 ml)	68.5
L	95°	48	toluene (10 ml)	68.5
M	Room Temp.	20	toluene (10 ml)	15.5
N	80°	20	cyclohexane (10ml)	61.6
O	40°	20	absolute ethanol (10 ml)	65.0
P	120°	20	without solvent	5.8
Q	95°	20	toluene (3 ml)	9.1

[a]Ratio of S^{-2} to $Br(CH_2)_5Br$ = 1.6 : 1.0. [b]Yields (± 1.5) Based on Recovered Starting Material.

The highest yield of pentamethylene sulfide was obtained when a mixture of 1,5-dibromopentane and the S^{-2}/Al_2O_3 complex was slurried at 95°C for 20 hours in 10ml of toluene (condition K, Table I-20).

The volume of solvent used in these reactions is important. When 1,5-dibromopentane and the 2.42 x 10^{-3} mol S^{-2}/g solid were slurried at 95°C for 20 hours with 3 ml of toluene, the stirring became erratic over time. After 10 hours of stirring, the reaction mixture became slightly gooey because the solvent had evaporated, and this result in a poor mixing of the reagents. This reaction afforded only 9.1% of product (Condition Q, Table I-20). When the 1,5-dibromopentane - S^{-2}/Al_2O_3 slurry was refluxed in cyclohexane for 20 hours at 80°C instead of toluene at 95°C for the same length of time, the yield of pentamethylene sulfide was reduced to 61.6% (compare Conditions K and N, Table I-20). Either the use of toluene as the solvent or higher reaction temperature was more favored. Stirring the dihalide and S^{-2}/Al_2O_3 without solvent was ineffective, yielding only 5.8% of pentamethylene sulfide.

When the reaction was run in absolute ethanol for 10 hours at 40°C, pentamethylene sulfide was generated in 65.0% yield. Because Na_2S is insoluble in toluene and cyclohexane, the reaction between the alkyl dihalide and sulfide in these solvents occurred on the surface of alumina. However, when ethanol was used as the solvent, the cyclization reaction may have occured in solution because the sulfide may have been "stripped" off the alumina due to its solubility in ethanol. See Figure I-4 (page 34). To corroborate this hypothesis, a separate reaction was carried out between 1,5-dibromopentane (1.6 mmol) and sodium sulfide nonahydrate (1.0 mmol) in 15 ml of

absolute ethanol at 40°C for 10 hours, but without alumina. Pentamethylene sulfide was formed in 48.4% yield. Thus it is possible that a great deal of the chemistry occured in solution.

When 1,5-dibromopentane was treated with sodium sulfide nonahydrate at 70°C for 10 hours in 15 ml of toluene, again in the absence of alumina, the cyclic sulfide was formed in only 5% yield.

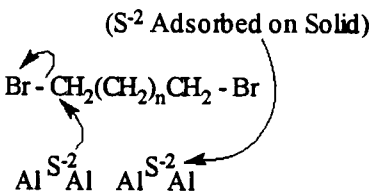


Figure I-4. (a) Reaction of Alkyl Dihalide with S^{-2}/Al_2O_3 in Toluene.

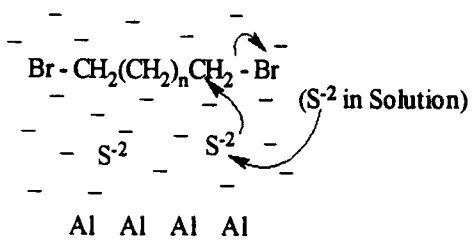


Figure I-4. (b) Reaction of Alkyl Dihalide with S^{-2}/Al_2O_3 in Absolute Ethanol.

A plot of product yield of pentamethylene sulfide versus the duration of reaction for reactions run at 95°C in 10 ml of toluene is informative and is presented in Figure I-5. It can be seen from the plot in Figure I-5 that not only does the yield of product increase as a function of time, but appears to do so in an exponential fashion, as expected.

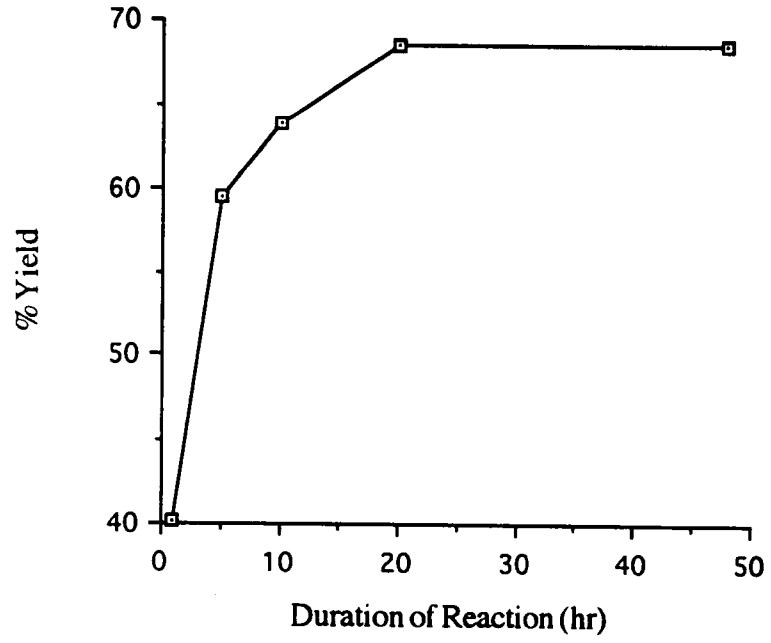


Figure I-5. Plot of % Yield of Pentamethylene Sulfide versus the Duration of Reaction under Condition K, Table I-20 (page 32).

Experiments were also run to determibe what effect temperature had on the reaction. Not surprisingly, the yield of pentamethylene sulfide dropped from 68.5%, when the reaction was run at 95°C, to 15.5%, when was run at room temperature.

The effect that different concentrations of S^{-2} had on the reaction of 1,5-dibromopentane with S^{-2}/Al_2O_3 was also examined. The results are shown in Table I-21. Of the various concentrations of sulfide on alumina used for the cyclization of 1,5-dibromopentane under condition K in Table I-20 (page 32), the 2.42 x 10^{-3} mol S^{-2}/g solid complex produced the highest yield of pentamethylene sulfide. As shown in Figure I-6, the yield of pentamethylene sulfide went up as the concentration of S^{-2} increased then decreased rapidly, and then decreased more gradually. Where the yield of product has dropped, the adjacent thiolates may be too close to each other, thus inhibiting their subsequent reaction with 1,5-dibromopentane.

Table I-21. The Effect of S^{-2} Loading on the % Yield of Pentamethylene Sulfide in the Reaction of 1,5-Dibromopentane with S^{-2}/Al_2O_3(110°C) under Condition K.

mol S^{-2}/g solid	% Yield[a]
5.04×10^{-4}	50.3
7.52×10^{-4}	56.8
2.42×10^{-3}	68.5
2.95×10^{-3}	65.0
3.50×10^{-3}	52.4
4.85×10^{-3}	50.0

[a]Yield = Isolated yield (± 1.5) of pentamethylene sulfide.

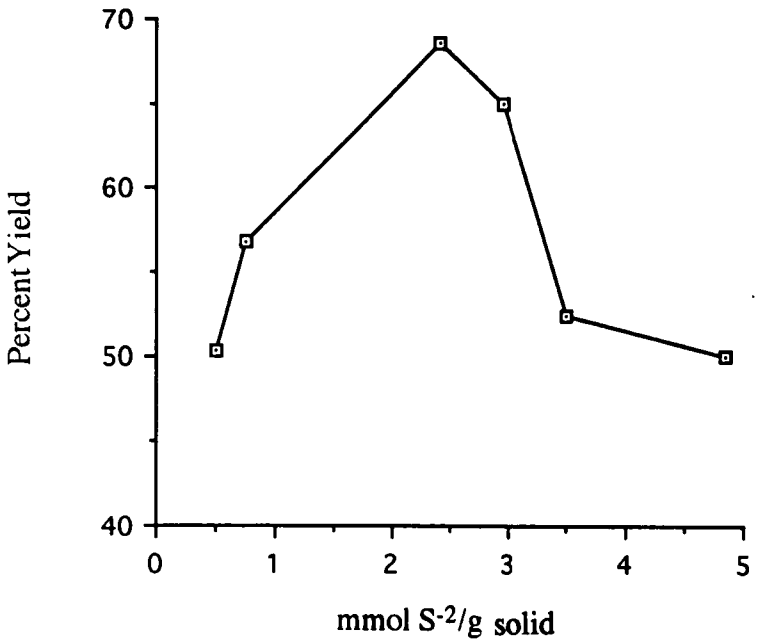


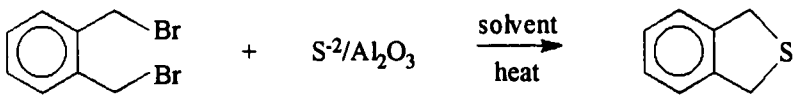
Figure I-6. Plot of % Yield of Pentamethylene Sulfide versus the Concentration of Sulfide on Alumina.

Because the reaction of 1,5-dibromopentane with S^{-2} on alumina gave pentamethylene sulfide in fairly good yield, a series of other dibromoalkanes, α,α'-dibromo-*o*-xylene, 1,6-dibromohexane, 1,4-dibromobutane, 1,3-dibromopropane, 1,2-

dibromoethane, 1,7-dibromoheptane, 1,8-dibromooctane, 1,9-dibromononane, 1,10-dibromodecane, 1,12-dibromododecane and 1,16-dibromohexadecane were examined. These reactions were run with various loadings of S^{-2} on Al_2O_3 in toluene because this solvent favored a higher yield of pentamethylene sulfide in the reaction of 1,5-dibromopentane with S^{-2}/Al_2O_3; ethanol was not used because, as noted earlier, sodium sulfide is leached off the solid by this solvent.

Reaction of α,α'-Dibromo-*o*-xylene with the S^{-2}/Al_2O_3 Complex.

Solutions of α,α'-dibromo-*o*-xylene were slurried with S^{-2}/Al_2O_3 at various concentrations of sulfide following the reaction sequence shown below in equation 20.



(20)

The sulfide concentrations that were used in these reactions were 5.04×10^{-4}, 2.42×10^{-3} and 2.92×10^{-3} mol S^{-2}/g solid (110°C). Conditions J, K O and P in Table I-20, page 32, were chosen for this study. The single product was isolated by preparative gas chromatography and identified as 1,3-dihydroisothianaphene by comparison of its ^1H NMR spectrum, GC retention time and MS with those of the known compound. The effects of the different concentrations of sulfide on alumina and the various reaction conditions on the product yield of 1,3-dihydroisothianaphene are listed in Table I-22.

The highest yield of 1,3-dihydrothianaphene was 68.2%, obtained when the reaction was run with 2.42 x 10^{-3} mol S^{-2}/g solid (100°C) at 95°C for 20 hours in 10 ml of toluene. When the reaction time was reduced to 10 hours, keeping the other reaction conditions the same, the yield decreased to 58.4%. However, the absence of solvent (Condition O, Table I-20, page 32) proved to be detrimental to the reaction, yielding 1,3-dihydroisothianaphene in only 30.6% yield.

Table I-22. The Effect of Sulfide Concentration and Various Reaction Conditions on the Yield of 1,3-Dihydroisothianaphene in the Reaction of α,α'-Dibromo-o-xylene with S^{-2}/Al_2O_3.[a]

				mol S^{-2}/g solid		
				$5.04x10^{-4}$	$2.42x10^{-3}$	$2.92x10^{-3}$
Condition	Rxn temp	Rxn. duration	Solvent (ml)	Yield[b] %	Yield[b] %	Yield[b] %
I	95°C	10 hr	10 ml toluene	51.4	58.4	50.6
J	95°C	20 hr	10 ml toluene	63.8	68.2	64.8
N	95°C	48 hr	10 ml toluene	63.8	68.2	64.8
O	120°	20 hr	without solvent	18.6	28.6	12.8

[a]Ratio of S^{-2} to α,α'-Dibromo-o-xylene = 1.6 : 1.0. [b]Yield = Isolated yield (± 1.5) of 1,3-Dihydroisothianaphene.

The results in the presence and absence of solvent are interesting. The absence of solvent always afforded the product in the lowest yield at all loadings of S^{-2} on Al_2O_3.

Thus, solvent provides an enhancement of the rate of the reaction. The solvent allows for better diffusion of the substrate on the surface and permits the intermediate thiolate to exist in an extended conformation, thus allowing the cyclization reaction to occur. None of these effects is possible in the absence of solvent (Figure I-7).

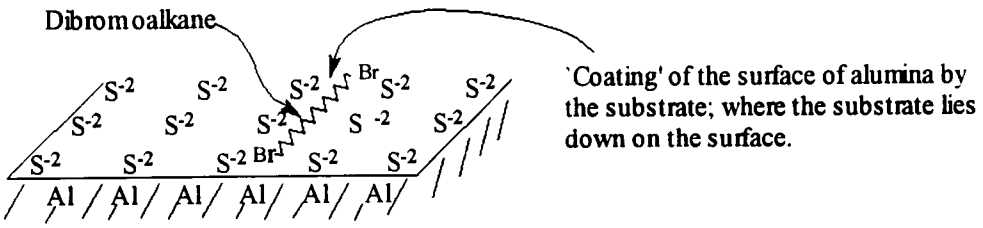


Figure I-7. (a) Reaction of Dibromoalkane with S^{-2}/Al_2O_3 Without Solvent.

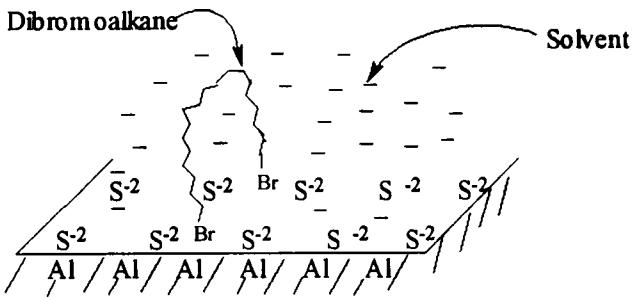


Figure I-7. (b) Reaction of Dibromoalkane with S^{-2}/Al_2O_3 in the Presence of Solvent

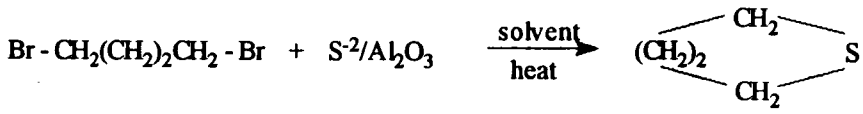
Reaction of 1,4-Dibromobutane with the S^{-2}/Al_2O_3 Complex.

The reaction of 1,4-dibromobutane with S^{-2}/Al_2O_3 was carried out by using the slurry method (eq 21, page 41). As before, a variety of reaction conditions and sulfide

concentrations were employed. The product was isolated by preparative GC and identified as tetrahydrothiophene by comparison of its ^1H NMR spectrum, GC retention time and MS with those of known tetrahydrothiophene. The results of these studies are summarized in Table I-23.

It can be seen from Table I-23 that employing condition K with the 4.85×10^{-3} mol S^{-2}/g Al_2O_3 gave by far the best results (44.7% of tetrahydrothiophene). Also, when considering only the first three concentrations of S^{-2}/Al_2O_3, reactions run for 20 hours gave a better yield of product than reactions run for 10 hours. When the reaction was performed without solvent, the yields were significantly lower as has been seen in previously described reactions.

S^{-2}/Al_2O_3 with a higher concentration of sulfide per gram of alumina (4.85×10^{-3} mol S^{-2}/g solid) was also treated with $Br(CH_2)_4Br$ in an attempt to increase the yield of tetrahydrothiophene because the best yield of tetrahydrothiophene was only 9.8% with the three lower concentrations of S^{-2} on alumina. Surprisingly, the yield for the isolated tetrahydrothiophene increased dramatically to 44.7%. Significantly, the new batch of the complex was used immediately after preparation, while the 2.92×10^{-3} mol S^{-2}/g solid, 5.04×10^{-4} mol S^{-2}/g solid and 2.42×10^{-3} mol S^{-2}/g solid complexes had been stored under argon for 4 weeks prior to use. In addition, the latter three complexes had also been exposed to air briefly (long enough to do 10 transfers of the complex used in reactions discussed previously). This may likely have caused the complex to readsorb moisture from the air, thus retarding the "effectiveness" of the complex.



(21)

Table I-23. The Effect of Sulfide Concentration and Reaction Conditions on the Yield of Tetrahydrothiophene in the Reaction of 1,4-Dibromobutane with S^{-2}/Al_2O_3.[a]

				mol S^{-2}/g Solid			
				5.04×10^{-4}	2.42×10^{-3}	2.92×10^{-3}	4.85×10^{-3}
Condition	Rxn temp.	Rxn. duration	Solvent (ml)	Yield[b]	Yield[b]	Yield[b]	Yield[b]
I	95°C	10 hr	10 ml toluene	6.2	7.8	8.4	N/A[c]
J	95°C	20 hr	10 ml toluene	7.6	9.0	9.8	44.7
O	120°C	20 hr	without solvent	3.0	3.2	4.8	N/A[c]

[a] Ratio of $Br(CH_2)_4Br$ to S^{-2} = 1.0 : 1.2. [b]Yield = Isolated yield (± 1.5) of tetrahydrothiophene. [c] Reaction was not performed.

An experiment was also performed to see if the yield of tetrahydrothiophene would be affected if the freshly prepared complex were deliberately exposed to air prior to its use in the reaction. After the newly-prepared 4.85 x 10^{-3} mol S^{-2}/g solid complex had been exposed to air for three hours, it was then reacted with 1,4-dibromobutane for 20 hours in 10 ml at 95°C. The yield of tetrahydrothiophene, corrected for unreacted starting material, was found to be 23.4%. 58.5% of unreacted 1,4-dibromobutane was also recovered from this reaction, compared to only 30.1% of unreacted 1,4-dibromobutane for the unexposed complex. It is therefore important to minimize the exposure of the S^{-2}/Al_2O_3 complex to air by storing under an inert atmosphere. The reagent should most likely only be used immediately after preparation.

Reaction of 1,3-Dibromopropane with the S^{-2}/Al_2O_3 Complex.

The reaction of 1,3-dibromopropane with S^{-2}/Al_2O_3 is expected to yield trimethylene sulfide (eq 22).

$$Br\text{-}(CH_2)_3\text{-}Br + S^{-2}/Al_2O_3 \longrightarrow \square S \qquad (22)$$

Because trimethylene sulfide has a relatively low boiling point of 94°C, the reaction of 1,3-dibromopropane with 4.85 x 10^{-3} mol S^{-2}/g solid was run with 10 ml of toluene for 20 hours at 85°C instead of 95°C in order to avoid the evaporation of the product from the reaction mixture. The isolated product, trimethylene sulfide, was formed in only 2.4% yield based on unreacted starting material. The structure was

confirmed by comparison of its ^1H NMR with that of trimethylene sulfide in the Stadler Index Reference.[20] Further conformation was provided by comparing the product's GC retention time and MS with those of a known compound. In addition to a low yield of product, there was also a considerable amount of recovered unreacted 1,3-dibromopropane (43%).

In an attempt to increase the yield of trimethylene sulfide, the reaction was repeated at 110°C in a tube sealed under vacuum for 10 hours in 10 ml of toluene (Table I-24). The isolated yield of trimethylene sulfide was 3.4% based on recovered starting material. When the reaction was repeated at 140°C for 20 hours, the isolated yield of trimethylene sulfide increased to 9.3% (Table I-24).

The lower yield of trimethylene sulfide (9.3%) in these reactions as compared to the yield of tetrahydrothiophene (44.7%) and pentamethylene sulfide (68.2%) in reactions described previously is consistent with the fact that four-membered rings are more difficult to form because of their larger ring strain (19.7 kcal/mol)[18] than that of the 5-membered (2.0 kcal/mol)[18] and 6-membered (0.0 kcal/mol)[18] rings.

Table I-24. The Effect of Reaction Conditions[a] on the Yield of Trimethylene Sulfide in the Reaction of 1,3-Dibromopropane with S^{-2}/Al_2O_3.[b]

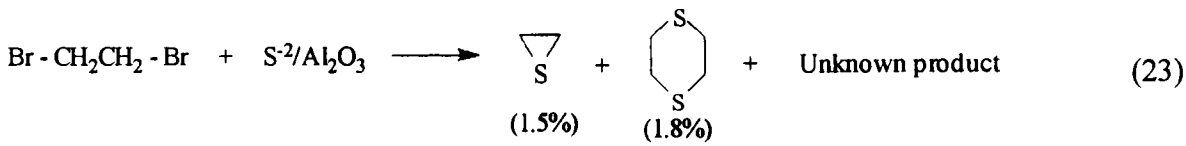
Reaction Duration	Reaction Temperatures	Yield (%)[c]
20 hrs.	85°C	2.4
10 hrs.	110°C (sealed tube)	3.4
20 hrs.	140°C (sealed tube)	9.3

[a]In 10 ml toluene. [b]The S^{-2}/Al_2O_3 complex used was 4.85 x 10^{-3} mol S^{-2}/g solid(100°C). The Ratio of $Br(CH_2)_3Br$ to S^{-2} = 1.0 : 1.2. [c]Yield = Isolated yield (± 1.5) of trimethylene sulfide.

Reaction of 1,2-Dibromoethane with the S^{-2}/Al_2O_3 Complex.

If it is difficult to synthesize trimethylene sulfide due to its ring strain, it ought to be even more difficult to make ethylene sulfide via the cyclization ring because ehylene sulfide has a ring strain of 19.9 kcal/mol.[18] The reaction of 1,2-dibromoethane with S^{-2}/Al_2O_3 was nonetheless examined next.

After treating 1,2-dibromoethane with 4.85 x 10^{-3} mol S^{-2}/g solid (1,2-dibromoethane : S^{-2} mole ratio = 1.0 : 1.2) in 10 ml of toluene in a sealed tube at 140°C for 20 hours, GC analysis of the crude product mixture showed four peaks (3 sharp peaks and one broad peak). Three of the peaks were due to ethylene sulfide, 1,2-dibromoethane and 1,4-dithiane by comparison to authentic compounds (eq 23). Not enough of the fourth compound could be isolated via preparative gas chromatography for identification. The yields were 1.5% of ethylene sulfide and 1.8% of 1,4-dithiane based on the 18.4% of unreacted 1,2-dibromoethane.

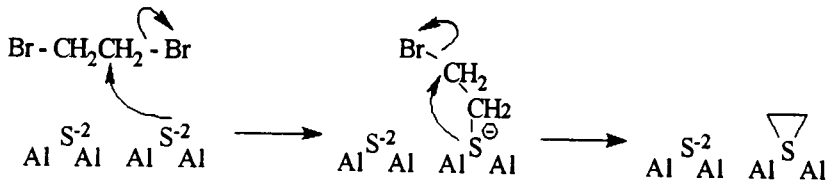


(23)

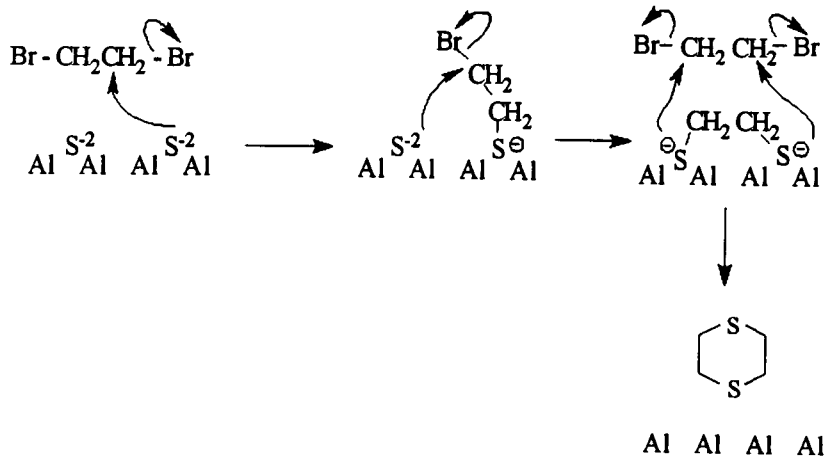
This is the first reaction in which a disulfide was isolated. Its formation, as well as that of ethylene sulfide, can be rationalized by chemistry shown in Scheme 3. Here, 1,2-dibromoethane is first attacked by S^{-2} in an S_N2 fashion to form a thiolate, followed by an intramolecular S_N2 attack by the S^{-1} end of the thiolate on the bromide end, leading to the formation of ethylene sulfide. To form the disulfide, 1,2-dibromoethane is first attacked by sulfide as before, but the thiolate intermediate reacts with an adjacent S^{-2} to

form $^{-}SCH_2CH_2S^{-}$, which reacts in two steps with another $Br\text{-}CH_2CH_2\text{-}Br$ to produce 1,4-dithiane.

Scheme 3. (a) Formation of Ethylene Sulfide.

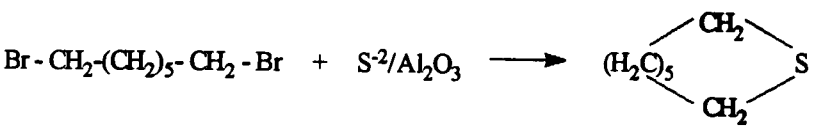


Scheme 3. (b) Formation of 1,4-Dithiane.



Reaction of 1,7-Dibromoheptane with the S^{-2}/Al_2O_3 Complex.

The desired reaction between 1,7-dibromoheptane and the S^{-2} on alumina will result in the eight-membered ring cyclic sulfide, heptamethylene sulfide (eq 24).



(24)

1,7-Dibromoheptane was reacted with a series of S^{-2}/Al_2O_3 complexes containing two sulfide loadings of S^{-2}: 5.04 x 10^{-4} and 2.95 x 10^{-3} mol S^{-2}/g solid(110°C). Because condition K in Table I-20, page 32, produced the best yields of cyclic sulfides from the reaction of 1,5-dibromopentane, α,α'-dibromo-*o*-xylene, and 1,4-dibromobutane with S^{-2}/Al_2O_3 respectively, it was also used for this study. The results are shown in Table I-25 below.

Table I-25. The Effect of Reaction Conditions on the Yield of Heptamethylene Sulfide in the Reaction of 1,7-Dibromoheptane with S^{-2}/Al_2O_3.[a]

mol S^{-2}/ g solid[a]	Rxn. temp.	Rxn Duration	Solvent	Yield %[b]
5.04 x 10^{-4}	110°C	20 hours	10 ml toluene	9.8
2.95 x 10^{-3}	110°C	20 hours	10 ml toluene	4.3

[a]The S^{-2}/Al_2O_3 Complex was prepared by activation at 110°C. The Ratio of $Br(CH_2)_7Br : S^{-2}$ = 1.0 : 1.8.
[b]Yield = Isolated yield (± 1.5) of heptamethylene sulfide.

The hexamethylene sulfide yields were 9.8% and 4.3% for the 5.04 x 10^{-4} and 2.95 x 10^{-3} mol S^{-2}/g solid, respectively. The 5.04 x 10^{-4} and 2.95 x 10^{-3} mol S^{-2}/g solid complexes that were used to run these reactions had been prepared a month earlier and had been exposed to the air eight times prior to use in these reactions. New batches of alumina complexes were, therefore, prepared and used immediately. Furthermore, the new batches of S^{-2}/Al_2O_3 complexes were prepared by activating the initial S^{-2}/Al_2O_3 complex mixture under vacuum at 95°C instead of 110°C, as described on page 16. The sulfide/alumina complexes prepared by dehydration at 95°C will be denoted as S^{-2}/Al_2O_3 (95°C) in order to differentiate them from the sulfide/alumina complexes prepared by dehydrating at 110°C. It was found that the hydrogen sulfide odor in the traps of the

vacuum system used to activate the complex was less pronounced when the complexes were dehydrated at 95°C compared 110°C. The various concentrations of the newly prepared S^{-2}/Al_2O_3 (95°C) complexes were 1.49 x 10^{-3}, 6.32 x 10^{-4} and 2.65 x 10^{-4} mol S^{-2}/g solid (95°C). As shown in Table I-26, the yields of desired product improved dramatically. The 1.49 x 10^{-3} mol S^{-2}/g solid complex gave the highest heptamethylene sulfide yield (47.1%) under the new reaction conditions. Interestingly, as the loading of sulfide on alumina decreased, the yield of heptamethylene sulfide also decreased. This is opposite to one of the premises which was the basis for this research project.

Table I-26. The Effect of Reaction Conditions on the Yield of Heptamethylene Sulfide in the Reaction of 1,7-Dibromoheptane with S^{-2}/Al_2O_3.[a]

mol S^{-2}/g solid	Rxn. temp.	Rxn Duration	Solvent	%Yield[b]
1.49 x 10^{-3}	95°C	20 hours	10 ml toluene	47.1
6.02 x 10^{-4}	95°C	20 hours	10 ml toluene	38.4
2.65 x 10^{-4}	95°C	20 hours	10 ml toluene	35.2

[a] The Ratio of $Br(CH_2)_7Br$ to S^{-2} = 1.0 : 1.8. [b]Yield = Isolated yield (± 1.5) of heptamethylene sulfide.

The dramatic increase in the yields of heptamethylene sulfide when the new batches of complexes were used may be due to the fact that the complexes had not been exposed to air prior to use. Dehydrating the initial comples at 95°C instead of 110°C may have also contributed to the increase in the yield of heptamethylene sulfide. As mentioned earlier, dehydrating the alumina and sodium sulfide nonahydrate complex at 95°C resulted in less hydrogen sulfide being lost to the traps.

If the same amount of sodium sulfide nonahydrate and alumina were used, activating the alumina/sulfide mixture at the higher temperature (110°C) should result in

less impregnation of sulfide on the alumina because the sulfide is lost as H_2S. As discussed earlier on page 18, sulfide reacts reversibly with water to form HS^- and OH^- anions. The newly formed HS^- then reacts with another molecule of water to form H_2S and another OH^- anion. Removal of the volatile H_2S during the activation of the alumina/sulfide mixture would shift the equilibrium of both reactions to the right. Activation at the higher temperatures should result in a greater loss of the volatile H_2S.

Because 2 OH^- are chemisorbed to Al_2O_3 every time one H_2S is lost, the lower yield of hexamethylene sulfide in the more activated solid may be due the effect of chemisorbed OH^- on the S^{-2}/Al_2O_3 complex, although the effect of chemisorbed OH^- on the nature of the S^{-2}/Al_2O_3 complex is not clear. A comparison of the reactions run on the "old" alumina and the freshly prepared alumina is shown in Table I-27.

Table I-27. Comparison Data for the Reaction of 1,7-Dibromoheptane with the S^{-2}/Al_2O_3 Complexes Prepared by Dehydrating the Sulfide/Alumina Mixture at Either 95°C or 110°C.[a]

mol S^{-2}/g solid used	Temp. of dehydration[b]	Alumina Quality[c]	Yield[d]
5.04×10^{-4}	110°C	old	9.8
2.95×10^{-3}	110°C	old	4.3
1.49×10^{-4}	95°C	fresh	47.1
6.02×10^{-4}	95°C	fresh	38.4
2.65×10^{-4}	95°C	fresh	35.2

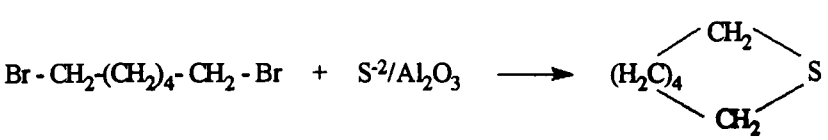
[a]The Ratio of $Br(CH_2)_7Br : S^{-2} = 1.0 : 1.8$. [b]The temperature at which the S^{-2}/Al_2O_3 complex was dehydrated. [c]Old=The alumina had been exposed to air eight times prior to use. Fresh =The alumina had been newly prepared. [d]Yield = Isolated yield of pentamethylene sulfide.

Reaction of 1,5-Dibromopentane with the S^{-2}/Al_2O_3 Complex Dehydrated at 95°C under Vacuum [S^{-2}/Al_2O_3 (95°C)].

The reaction of 1,5-dibromopentane with sulfide on alumina was repeated with the new batches of alumina complexes that were dehydrated at 95°C instead of 110°C (EXPERIMENTAL SECTION, page 83). The reactions were run at 95°C for 20 hours in 10 ml toluene (condition K, Table I-20, page 32). The yield of the pentamethylene sulfide increased from 68.5% to 79.2% (Table I-28, page 52) when 1.49×10^{-3} mol S^{-2}/g solid (95°C) was used. Reaction of 1,5-dibromopentane with the 6.02×10^{-4} mol S^{-2}/g solid (95°C) complex gave a yield of 55.1%. Dehydrating the complex at 95°C instead of 110°C may have contributed to the increase in the yield of pentamethylene sulfide to 79.2%. As mentioned earlier, dehydrating the alumina and sodium sulfide nonahydrate complex at 95°C resulted in less hydrogen sulfide in the traps than when dehydrated at 110°C. A comparison of the effects of the various S^{-2}/Al_2O_3 complexes have on the yield of pentamethylene sulfide are summarized in Table I-29, page 56.

Reaction of 1,6-Dibromohexane with the S^{-2}/Al_2O_3 Complex.

The synthesis of hexamethylene sulfide was performed by reacting 1,6-dibromohexane with S^{-2}/Al_2O_3 (eq 25).



(25)

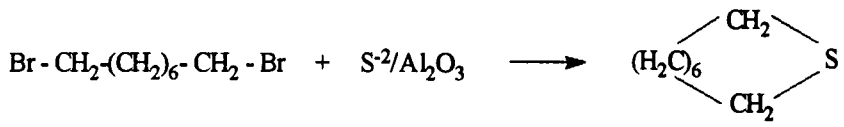
Reaction conditions J, K and P (Table I-20, page 32) were chosen, with loadings of sulfide on alumina of 5.04×10^{-4}, 2.42×10^{-3} and 2.92×10^{-3} mol S^{-2}/g solid (110°C) and 1.69×10^{-3} and 6.02×10^{-4} mol S^{-2}/g solid (95°C). The S^{-2}/g Al_2O_3 (95°C) complexes, however, were reacted with 1,6-dibromohexane using only condition K, Table I-20, page 32.

The single product was isolated by preparative gas chromatography and identified as hexamethylene sulfide by comparison of its ^{1}H NMR spectrum, GC retention time and MS to those of the known compound. The highest yield of hexamethylene sulfide was obtained by using condition K (Table I-28, page 52), with 1.49×10^{-3} mol S^{-2}/g solid (95°C). The best yield of hexamethylene sulfide from the reaction of 1,6-dibromohexane with S^{-2}/Al_2O_3 (110°C) complex was 52.5% (Table I-28, page 52). The S^{-2}/Al_2O_3 (95°C) complexes gave a higher yield of hexamethylene sulfide than the S^{-2}/Al_2O_3 (110°C) complexes did. It can also be concluded that longer reaction times are necessary for better yields (compare conditions J and K in Table I-28). Running the reaction without solvent is again detrimental to the product yield (condition P, Table I-28).

Reaction of 1,8-Dibromooctane with the S^{-2}/Al_2O_3 (95°C) Complex.

1,8-Dibromooctane in 10 ml of toluene was treated with 6.02×10^{-4} mol S^{-2}/g solid (95°C) and 1.49×10^{-3} mol S^{-2}/g solid (95°C) for 20 hours in order to prepare octamethylene sulfide (eq 26). The single product was identified as octamethylene sulfide (eq 26) by comparing its ^{1}H NMR spectrum and melting point with the ^{1}H NMR spectrum and melting point of octamethylene sulfide prepared by the procedure of

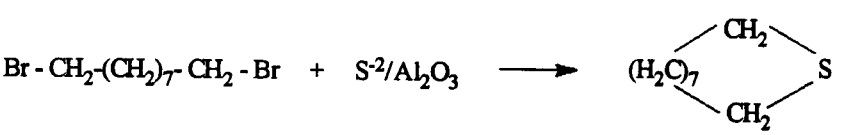
Mandolini *et al.*[8] The yields of octamethylene sulfide obtained from these reactions were 37.7% and 26.2% for the 6.02 x 10^{-4} and 1.49 x 10^{-3} mol S^{-2}/g solid (95°C) complexes, respectively (Entry 3, Table I-29, page 56).



(26)

Reaction of 1,9-Dibromononane with the S^{-2}/Al_2O_3 (95°C) Complex.

In order to synthesize nonamethylene sulfide, 1,9-dibromononane was slurried at 95°C with 7.52 x 10^{-4} mol S^{-2}/g solid (110°C) for 20 hours in 10 ml toluene (eq 27). The sole product was identified as nonamethylene sulfide by comparing its ^1H NMR spectrum and melting point to the ^1H NMR spectrum and melting point of the nonamethylene sulfide prepared separately by the method described by Mandolini *et al.*[8] Our procedure afforded nonamethylene sulfide in 1.4% yield relative to unreacted starting material. Repeating the reaction with the 1.49 x 10^{-3} mol S^{-2}/g solid (95°C) and the 6.02 x 10^{-4} mol S^{-2}/g solid (95°C) afforded the product in 12.6% and 15.7% yield, respectively, relative to recovered unreacted starting material (Entry 5, Table I-29, page 56).



(27)

Table I-28. Effect of Various Reaction Conditions on the Yield of Hexamethylene Sulfide According to Equation 18.[a]

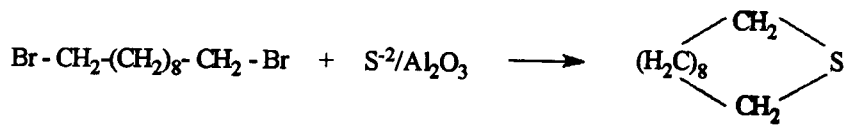
				mol S^{-2}/g solid				
				$5.04x10^{-4}$	$2.42x10^{-3}$	$2.92x10^{-3}$	$1.49x10^{-3}$	$6.02x10^{-4}$
Condition	Rxn temp.	Rxn. duration	Amount Solvent	Yield[b] (%)	Yield[b] (%)	Yield[b] (%)	Yield[c] (%)	Yield[c] (%)
J	95°C	10 hr	10 ml toluene	39.1	42.8	50.6	-	-
K	95°C	20 hr	10 ml toluene	42.0	49.6	52.5	62.4	59.7
P	120°C	20 hr	without solvent	18.2	20.3	24.6	-	-

[a] The ratio of $Br(CH_2)_6Br$: S^{-2} = 1.0 : 1.8. [b] The S^{-2}/Al_2O_3 complexes used were prepared by dehydration of the sulfide and alumina mixture at 110°C under vacuum. Yield = Isolated yield of hexamethylne sulfide. [c] The S^{-2}/Al_2O_3 complexes used were prepared by dehydration of the sulfide and alumina mixture at 95°C under vacuum.

The reaction of 1,9-dibromononane with the S^{-2}/Al_2O_3 (95°C) complex having the lower sulfide loading (6.02×10^{-9} mol S^{-2}) resulted in higher yields of nonamethylene sulfide than the 1.49×10^{-3} mol S^{-2}/g solid (95°C) complex did. This result is consistent with the hypothesis that, if the average distance between adjacent sulfide ions adsorbed on alumina is greater than the average length of the 1,9-dibromononane chain, cyclization will predominate over the intermolecular reaction, as described earlier on page 11. While the highest yield of pentamethylene sulfide was obtained when the loading of sulfide was 1.49×10^{-3} mol S^{-2}/g solid (95°C), the highest yield of nonamethylene sulfide was obtained when the loading of sulfide used was smaller (6.02×10^{-4} mol S^{-2}/g solid (95°C)).

Reaction of 1,10-Dibromodecane with the S^{-2}/Al_2O_3 (95°C) Complex.

The reaction was carried out by slurrying 1,10-dibromodecane with the S^{-2}/Al_2O_3 (95°C) complex (eq 28). The sole product, decamethylene sulfide, a waxy solid, was characterized by comparing its ^1H NMR spectrum and melting point with that of decamethylene sulfide prepared independently by the method described by Mandolini *et al.*[8] The best yield of decamethylene sulfide (12.4% relative to unreacted starting material) was produced when 1,10-dibromodecane was reacted with S^{-2}/Al_2O_3 complex containing 6.02×10^{-4} mol S^{-2} per gram of solid. When the reaction was repeated with the 1.49×10^{-3} mol S^{-2}/g solid (95°C) complex, the yield of decamethylene sulfide was reduced to 9.0%. The results are summarized in Table I-29, entry 6, page 56.

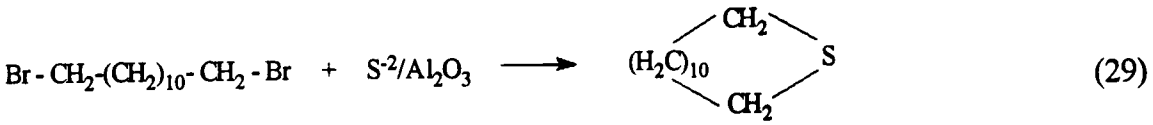


(28)

The reaction of 1,10-dibromodecane with S^{-2}/Al_2O_3 (95°C) complex containing the lower loading of sulfide (6.02 x 10^{-4} mol S^{-2}/g solid) gave a better yield in this case. The reaction of 1,10-dibromodecane with 7.52 x 10^{-4} mol S^{-2}/g solid (110°C), however, yielded only 2.2% of decamethylene sulfide (Table I-29, page 56). Clearly, the temperature at which S^{-2}/Al_2O_3 is activated is critical to the success of the cyclization reaction.

Reaction of 1,12-Dibromododecane with the S^{-2}/Al_2O_3 (95°C) Complex.

1,12-Dibromododecane was slurried with 7.52 x 10^{-4} mol S^{-2}/g solid (110°C), 6.02 x 10^{-4} mol S^{-2}/g solid (95°C) and 1.49 x 10^{-3} mol S^{-2}/g solid (95°C) at 95°C for 20 hours in 10 ml of toluene (eq 29). The single product, which was a waxy solid, was identified as dodecamethylene sulfide; its ^1H NMR spectrum and melting point were identical to those of material independently prepared by the procedure described by Mandolini *et al.*[8] The results are sumarized in Table I-29, Entry 6, Page 60.



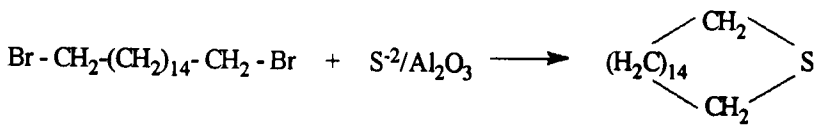
(29)

The reaction of 1,12-dibromododecane with the 6.02 x 10^{-4} mol S^{-2}/g solid (95°C) complex gave the best yield of dodecamethylene sulfide (20.4%). Reaction of the 1,12-dibromododecane with the more concentrated S^{-2}/Al_2O_3 (1.49 x 10^{-3} mol S^{-2}/g solid) gave a lower yield of dodecamethylene sulfide (15.6%), while the reaction with the 7.52 x 10^{-4} mol S^{-2}/g solid (110°C) resulted in only 3.4% of dodceamethylene sulfide (Table I-29,

page 56). As described before, sulfide concentration and Al_2O_3 activation temperature are critical to the success of the cyclization reaction.

Reaction of 1,16-Dibromohexadecane with the S^{-2}/Al_2O_3 (95°C) Complex.

1,16-Dibromohexadecane was treated with 7.52 x 10^{-4} mol S^{-2}/g solid (110°C), 6.02 x 10^{-4} mol S^{-2}/g solid (95°C) and 1.49 x 10^{-3} mol S^{-2}/g solid (95°C) at 95°C in 10 ml of toluene for 20 hours (eq 30). The expected product, hexadecamethylene sulfide, was formed in each reaction; its structure was confirmed by comparing its ^{1}H NMR spectrum and melting point with hexadecamethylene sulfide prepared independently by the method used by Mandolini *et al.*[8] The results of these reactions are reported in Table I-29 (page 56).



(30)

The best yield of hexadecamethylene sulfide, 28.6%, was produced when 1,16-dibromohexadecane was slurried with the alumina complex having with the lowest sulfide concentration of 6.02 x 10^{-4} mol S^{-2}/g solid (95°C). The reaction of 1,16-dibromohexadecane with 1.49 x 10^{-3} mol S^{-2}/g solid (95°C) and 7.52 x 10^{-4} mol S^{-2}/g solid (110°C) resulted in 19.1% and 4.2% hexadecamethylene sulfide, respectively. These trends are identical to those observed with 1,12-dibromododecane.

Table I-29. Data for the Reaction of Different Dibromoalkanes with S^{-2}/Al_2O_3 Complexes of Varying Sulfide Loadings.[a]

			mol S^{-2}/g solid		
			6.02×10^{-4}	1.49×10^{-3}	7.52×10^{-4} new batch
Entry	Dibromoalkane	Rxn. Condition[b]	Yield[c] (%)	Yield[c] (%)	Yield[d] (%)
1	1,5-dibromopentane	K	55.1	79.2	N/A[e]
2	1,6-dibromohexane	K	59.7	62.4	N/A[e]
3	1,7-dibromoheptane	K	38.4	47.1	N/A[e]
4	1,8-dibromooctane	K	37.7	26.2	0.9
5	1,9-dibromononane	K	15.7	12.6	1.4
6	1,10-dibromodecane	K	12.4	9.0	2.2
7	1,12-dibromododecane	K	20.4	15.6	3.4
8	1,16-dibromohexadecane	K	28.6	19.1	4.2

[a] The ratio of $Br(CH_2)_nBr$ to S^{-2} = 1.0 : 1.8 (where n = 5,6 and 7); The ratio of $Br(CH_2)_mBr$ to S^{-2} = 1.0 : 1.9 (where m = 8,9,10,12 and 16)
[b] Condition K: Reaction temperature = 95°C, Reaction duration = 20 hours and amount of solvent used = 10 ml toluene. [c] The S^{-2}/Al_2O_3 complexes used were prepared by dehydration of the sulfide and alumina mixture at 95°C under vacuum. Yield = Isolated yield (± 1.5) of the corresponding cyclic sulfides.
[d] The S^{-2}/Al_2O_3 complex used were prepared by dehydration of the sulfide and alumina mixture at 110°C under vacuum. N/A = reaction was not performed. Yield = Isolated yield (± 1.5) of the corresponding cyclic sulfides.

The data in Table I-29 summarize the results for numerous cyclizations run on fresh S^{-2}/Al_2O_3 (95°C); for comparison purposes data obtained on S^{-2}/Al_2O_3 (110°C) are also presented. The data for S^{-2}/Al_2O_3 (95°C) are also presented in graphical form (Figure I-8). The plot of % yield of the cyclic sulfide versus the ring size of the two respective sulfide loadings (6.02×10^{-4} mol S^{-2}/g solid and 1.49×10^{-3} mol S^{-2}/g solid) shows similar trends (Figure I-8). The higher sulfide loading show increased yields at shorter chain lengths (i.e., the 5, 6 and 7 carbon chain lengths), while the lower loading shows increased yields for the longer chain lengths (i.e., the 8, 9, 10, 12 and 16 carbon chain lengths). These results are not unexpected. The higher loading will favor small ring formation and inhibit large ring formation. Lower loadings should and do favor larger ring formation. These results are consistent with the hypothesis (page 11) that, if the intermediate thiolates are localized as far from each other as possible, cyclization will predominate over intermolecular polymerization.

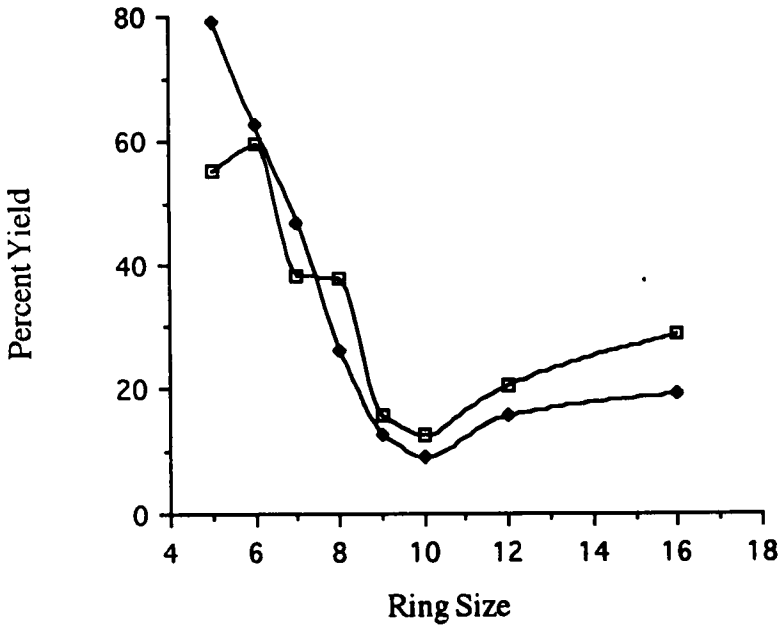


Figure I-8. Plot of % Yield of Cyclic Sulfide versus Ring Size for (a) squares for 6.02×10^{-4} mol S^{-2}/g solid and (b) filled diamonds for 1.49×10^{-3} mol S^{-2}/g solid.

CHAPTER 4

CONCLUSION

A number of cyclic organosulfides were prepared by the treatment of dibromoalkanes with the S^{-2}/Al_2O_3 complexes. The reactions were run by the slurry method which is a simple, one-pot procedure. The cyclic sulfides prepared by the slurry method are presented in Table I-30, page 60. Concentration of S^{-2} per gram of alumina used in producing the best yields of the cyclic organosulfides are also presented in Table I-30, page 60. Of the various reaction conditions used, condition K (Table I-20, page 32), where the mixture of dibromoalkane and S^{-2}/Al_2O_3 complex is slurried at 95°C in 10 ml toluene for 20 hours, gave the best yield of cyclic sulfide. The optimum concentration of S^{-2} per gram of alumina depended on the chain length of the dibromoalkane used. The S^{-2}/Al_2O_3 complex prepared by dehydrating the sulfide on alumina at 95°C gave better yields of cyclic organosulfides than when dehydrated at 110°C. Freshly made S^{-2}/Al_2O_3 also gave optimal yields of products.

A plot of the highest percent yield of cyclic organosulfide versus the ring size of the product is pictured in Figure I-9, page 59. The yield of cyclic sulfide depends strongly on chain length. The yields of ethylene sulfide, trimethylene sulfide and tetrahydrothiophene are low (1.5%, 9.3%, and 44.7%, respectively) and are consistent with the reactions producing rings with large ring strains. It ought to be difficult to cyclize thiolates which yield rings with large ring strains. The ring strains for ethylene sulfide and trimethylene sulfide are 19.9 and 19.7 kcal/mol, respectively.[18] The plot

reaches a maximum at ring size = 6 (Figure I-9). This is expected because pentamethylene sulfide has a ring strain energy of 0 kcal/mole.[18]

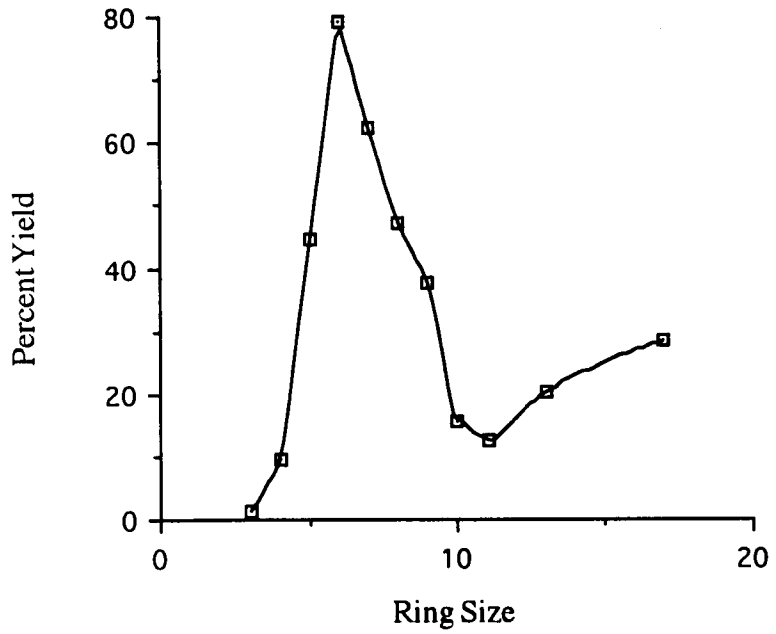


Figure I-9. The Percent Yield of Cyclic Organosulfide versus the Ring Size of Cyclic Organosulfide. In Each Case the Higest Yield of the Cyclic Organosulfide is Reported.

The plot approaches a minimum at ring size = 10. This trend for the cyclic sulfide formation by the reaction of dibromoalkanes and S^{-2}/Al_2O_3 complex is similar to the trend observed by Mandolini *et al.*[8] for the reaction of dibromoalkanes and $Na_2S{\cdot}9H_2O$ in HMPT. This is expected because it is difficult to cyclize 9, 10 and 11 membered rings due to the presence of transannular interactions in these ring sizes. The transannular interaction decreases as the ring size becomes larger than 11.

Table 30. Formation of Cyclic Sulfides from Dibromoalkanes and S^{-2}/Al_2O_3 Complex.

Dibromoalkane	Cyclic Sulfide	mol S^{-2}/g solid (°C)[a]	% yield[b]
1,2-dibromoethane	ethylene sulfide +	4.85 x 10^{-3}(110°C)	1.5
	1,4-dithiane[c]	4.85 x 10^{-3}(110°C)	1.8
1,3-dibomopropane	trimethylene sulfide	4.85 x 10^{-3}(110°C)	9.3
1,4-dibromobutane	tetrahydrothiophene	4.85 x 10^{-3}(110°C)	44.7
1,5-dibromopentane	pentamethylene sulfide	1.49 x 10^{-3}(95°)	79.2
1,6-dibromohexane	hexamethylene sulfide	1.49 x 10^{-3}(95°C)	62.4
1,7-dibromoheptane	heptamethylene sulfide	1.49 x 10^{-3}(95°)	47.1
1,8-dibromooctane	octamethylene sulfide	6.02 x 10^{-4}(95°)	37.7
1,9-dibromononane	nonamethylene sulfide	6.02 x 10^{-4}(95°)	15.7
1,10-dibromodecane	decamethylene sulfide	6.02 x 10^{-4}(95°)	12.4
1,12-dibromododecane	dodecamethylene sulfide	6.02 x 10^{-4}(95°)	20.4
1,16-dibromohexadecane	hexadecamethylene sulfide	6.02 x 10^{-4}(95°)	28.6
ortho-dibromoxylene	1,3-dihydrobenzo[c]-thiophane	2.42 x 10^{-3}(110°C)	68.2

[a]Temperature at which S^{-2}/Al_2O_3 is activated. [b]The best yields (± 1.5) were reported. [c]Yield (± 1.5) of 1,4-dithiane.

Interestingly, the yields of cyclic sulfides also depend on sulfide loading on the alumina in addition to the chain length. For dibromoalkanes of eight carbons and above, as the concentration of S^{-2} goes down, the yield of the cyclic organosulfide increases. This can be seen in Table I-29, page 56. This result is consistent with the hypothesis that intermolecular polymerization that accompanies the intramolecular cyclization will be reduced if the sulfides are localized as far away from each other on the alumina as possible (Scheme 1, page 11). The complex with 6.02×10^{-4} mol S^{-2}/g solid (95°C), i.e. the S^{-2}/Al_2O_3 complex with the lowest sulfide concentration of all, gave the best yield of cyclic organosulfide.

In the case of 1,7-dibromoheptane, however, the opposite was true (Entry 3, Table I-29, page 56). Reaction with 1.49×10^{-3} mol S^{-2}/g solid (95°C) gave heptamethylene sulfide yield in 47.1% yield, whereas reaction with the 6.02×10^{-4} mol S^{-2}/g solid (95°C) gave the product in 38.4% yield. Reduction in the concentration of sulfide per gram of alumina below the optimum sulfide concentration of 1.49×10^{-3} mol S^{-2}/g solid results in a lower yield of heptamethylene sulfide (Table I-27, page 48). The dibromoalkanes with n= 6 behave similarly.

The initial target of our research was to see if S^{-2}/Al_2O_3 is a more effective medium for cyclization of dibromoalkanes than the solution and to see how varying the concentration of sulfide on alumina affected the yield of the cyclic organosulfides. These goals were attained. In addition, other features of the reactions are noteworthy. The advantages of synthesizing cyclic organosulfides from dibromoalkanes and the S^{-2}/Al_2O_3 complexes using the slurry method, for example, are its low cost, the availability of

alumina, the avoidance of using an aqueous phase, its simplicity, and convenience in product work-up. This method is a worthy alternative procedure to solution counterparts, particularly for small-scale preparations. It is also a valuable addition to the collection of synthetic tools for preparing medium to large sized cyclic sulfides.

CHAPTER 5

OTHER SOURCES OF S^{-2}

With a series of dibromoalkanes of various chain length in hand, our attention was turned to the preparation of the cyclic organosulfides on alumina using other sources of sulfide. Two other sources of sulfide were used: *bis*(tributyltin)sulfide and thioacetamide (Figure I-10). As with the previously described reactions various conditions were used in attempts to optimize the yield of the cyclic organosulfides.

$Bu_3SnSSnBu_3$	CH_3CSNH_2
***Bis*(tributyltin)sulfide**	**Thioacetamide**

Figure I-10. The Two Other Sources of Sulfides: (a) *Bis*(tributyltin)sulfide, (b) Thioacetamide.

A. *Bis*(tributyltin)sulfide

Background

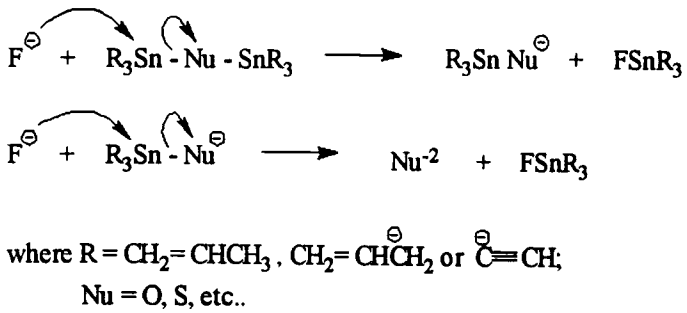
In 1987, Harpp and Gingras[11,14,15] discovered a method to prepare organosulfides by use of a fluorodestannylation reaction, permitting the synthesis of a host of organosulfides in high yield under mild and neutral conditions (eq 31). They also found that cyanide ion performed comparably (cyanodestannylation) to fluoride, although it was not as reactive as fluoride.

$R_3"Sn\text{-}S\text{-}SnR_3" + 2RX + 2\ Nu^- \rightarrow R\text{-}S\text{-}R + 2\ R_3"Sn\text{-}Nu + 2\ X^-$ (31)

where R = alkyl, R" = Ph, Bu, Me; X = Cl, Br, I; Nu^- = CN^-, F^-.

They later reported[14,15] that fluoride ion can combine with organotin oxides, sulfides, and selenides to liberate the corresponding anion (Scheme 4). The fluoride ion can also combine with organostannanes such as $Bu_3SnCH_2\text{-}CH\text{-}CH_2SnBu_3$ and $Bu_3Sn\text{-}C\equiv CH$ to liberate the corresponding $CH_2{=}CH\text{-}CH_2^{\ominus}$, and $^{\ominus}C\equiv CH$ anions.

Scheme 4. Fluorodestannylation of Organotins.[11,14,15]



The sources of fluoride ion that were effective as nucleophiles were tetrabutyl ammonium fluoride (TBAF), tetrabutylammonium fluoride trihydrate ($TBAF \cdot 3H_2O$) and cesium fluoride (CsF). Potassium fluoride (with and without 18-crown-6) did not destannylate the organotinsulfides successfully. A sample of the successful syntheses of sulfide are listed in Table I-31.

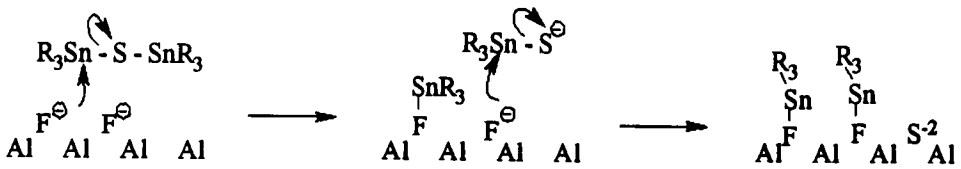
Table I-31. Synthesis of Organosulfides by the Reaction of Alkyl Halides with Organotin sulfides and Fluoride by the Method of Harpp and Gingras.[11,14,15]

Halide	Organotin	F^- or CN^-	Sulfide	% Yield
$PhCH_2Br$	$(Bu_3Sn)_2S$	$TABF \cdot 3H_2O$	$(PhCH_2)_2S$	85
$PhCH_2Br$	$(Bu_3Sn)_2S$	TBACN	$(PhCH_2)_2S$	41
$CH_3(CH_2)_5Br$	$(Me_3Sn)_2S$	$CsF \cdot 18C6$	$(CH_3(CH_2)_5)_2S$	99
$PhCOCH_2Br$	$(Bu_3Sn)_2S$	CsF	$(PhCOCH_2)_2S$	98

The ability to utilize several sources of fluoride ion in these reactions led us to try the F^-/Al_2O_3 complex as the source of the fluoride ion in the fluorodestannylation reaction. F^-/Al_2O_3 complex can be prepared by the same methodology used in the preparation of S^{-2}/Al_2O_3 complex. The procedure for the preparation of F^-/Al_2O_3 complex is discussed in the EXPERIMENTAL SECTION.

Research was performed to determine the feasibility of using F^-/Al_2O_3 as the source of fluoride ion to liberate sulfide from its reaction with *bis*(tributyltin)sulfide. If F^- reacts with $(Bu_3Sn)_2S$ in the expected manner, the liberated sulfide will of course be deposited on the surface of alumina (Scheme 5). 1,5-Dibromopentane was chosen as the substrate because it gave higher yields of product with S^{-2}/Al_2O_3 than any other dibromoalkane.

Scheme 5. Fluorodestannylation of Organotinsulfide by F^-/Al_2O_3



Results and Discussion

The concentrations of fluoride used in these reactions were 2.14 x 10^{-2} mol F^-/g solid and 3.28 x 10^{-3} mol F^-/g solid. The calculations used to determine the number of moles of fluoride absorbed on each gram of solid are described in the EXPERIMENTAL SECTION. To the F^-/Al_2O_3 complex was added *bis*(tri-*n*-butyltin)sulfide by dropwise injection. Then 1,5-dibromopentane dissolved in acetonitrile was added and the resulting mixture slurried for 5 hours at room temperature under argon. The reagents were reacted in a 2:1:1 mole ratio of F^- to *bis*(tri-*n*-butyltin)sulfide to 1,5-dibromopentane. The single product was identified as pentamethylene sulfide by the methods described previously. The yield of pentamethylene sulfide was very low in both cases, being 5% for the 2.14 x 10^{-2} mol F^-/g solid and 3% for the 3.28 x 10^{-3} mol F^-/g solid.

Other attempts that were made to optimize the yield of pentamethylene sulfide deserve comment, although they were not very successful. When the reaction time was increased to 24 hours, 2.14 x 10^{-2} mol F^-/g solid afforded pentamethylene sulfide in 6% yield whereas 3.28 x 10^{-3} mol F^-/g solid afforded the product in 3% yield. Changing the mole ratio of the starting materials to 1:1:1 [F^-:1,5-dibromopentane:S^{-2}] and keeping the reaction time at 24 hours, resulted in 2% of pentamethylene sulfide. When the solvent was changed to dimethyl formamide, reaction of 1,5-dibromopentane with 2.14 x 10^{-2} mol F^-/g solid and *bis*(tri-*n*-butyltin)sulfide at room temperature for 24 hours, only a trace amount of pentamethylene sulfide was detected by gas chromatography.

The results indicate that the reaction of *bis*(tri-*n*-butyltin)sulfide and F^-/Al_2O_3 with 1,5-dibromopentane is not a useful method to make pentamethylene sulfide. Thus, attention was turned to thioacetamide as a source of sulfide.

B. Thiacetamide

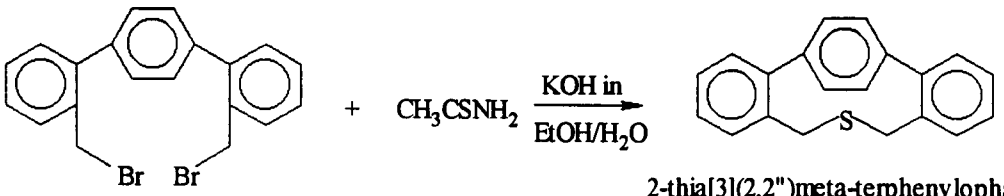
Background

Thiacetamide has been used for decades in qualitative analysis as a reagent for the precipitation of metal sulfides. The procedure involves the addition of approximately 1 ml of the 0.1 M metallic cation solution to be analyzed (e.g., $AgNO_3$, $Pb(NO_3)_2$, $CuSO_4$, etc.) into a test tube. To this is added two drops of 1.0 M thioacetamide dissolved in water. The solution is then heated to boiling in a water bath for five minutes. The thioacetamide hydrolyzes in hot water to produce aqueous H_2S (eq 32),[12] which then reacts with the metal cation to form an insoluble precipitate.

$$CH_3CSNH_2 + H_2O \rightarrow CH_3CONH_2 + H_2S \qquad (32)$$

Thioacetamide is thus a source of sulfide. Only recently, however, has thiacetamide been utilized as a source of sulfide for cyclization reactions to yield cyclic sulfides in organic solvents. Vögle *et al.*[16] synthesized 2-thia[3](2,2")*meta*-terphenylophane in 19% yield, for example, from the reaction of 2,2"-

bis(bromomethyl)*meta*-terphenyl with thioacetamide in refluxing benzene/ethanol (2:1) and KOH in ethanol/water (20:1) (eq 33).



(33)

2,2"-*bis*(bromomethyl)meta-terphenyl

2-thia[3](2,2")meta-terphenylophane

The 19% yield is attractive when compared to the lower yield (11%) obtained by the reaction of 2,2"-*bis*(bromomethyl)*meta*-terphenyl with $Na_2S \cdot 9H_2O$ in ethanol/benzene (4:1).[17]

It should be noted that the base, KOH, is necessary for the formation of sulfide ions in the thioacetamide method. Since unactivated alumina has a surface layer of hydroxyl groups, it could aid the hydrolysis of thioacetamide, resulting in the *in situ* formation of H_2S. If this is true, the reaction of an alkyl dibromide with thioacetamide and alumina will result in the formation of the corresponding cyclic sulfide. An investigation was carried out to see if this hypothesis is true.

Results and Discussions.

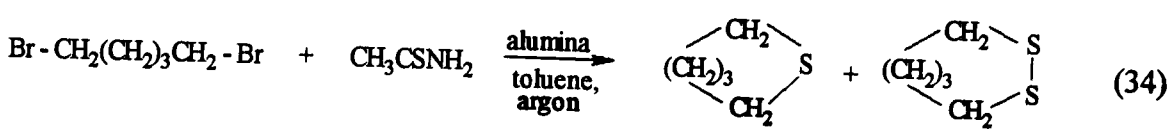
The reactions of dibromoalkane with thioacetamide and alumina were performed using the procedures discussed in detail in the EXPERIMENTAL SECTION. Identification and yield of products were determined by the methods already described.

Reaction of 1,5-Dibromopentane with Thioacetamide and Alumina.

This reaction was carried out by first dissolving 1.0 mmol of 1,5-dibromopentane in 10 ml of toluene in a round bottom flask. Thioacetamide and out-of-the-bottle (unactivated) alumina (neutral Brockmann 1) were then added, and the mixture stirred for 10 hours at the reflux temperature of toluene under argon. Various ratios of thioacetamide, 1,5-dibromopentane and alumina were used in an attempt to optimize the product yields. For example, 1.0 mmol, 2.0 mmol and 5.0 mmol of thioacetamide and 1.00 gram, 2.00 grams and 5.00 grams of alumina were used.

Two products were isolated by preparative gas chromatography and identified as pentamethylene sulfide and pentamethylene disulfide by comparison of their ^{1}H NMR spectrum to those in the Sadtler Index Reference.[20] The compounds were characterized further by analysis of their MS. The general reaction is outlined in Equation 34, and the results are summarized in Table I-32.

The highest yields of pentamethylene sulfide and disulfide, 28.8% and 31.2%, respectively, were achieved when 1.0 mmol 1,5-dibromopentane was reacted with 2.0 mmol of thioacetamide and 1.00 gram of alumina. Lowering the amounts of alumina to 1.0 mmol resulted in a higher yield of pentamethylene disulfide (compare entry B and D; compare A and F, Table I-32). When the amount of alumina used was increased to 5.00 grams the yield of both the sulfide and disulfide did not improve (entry E, Table I-32).



(34)

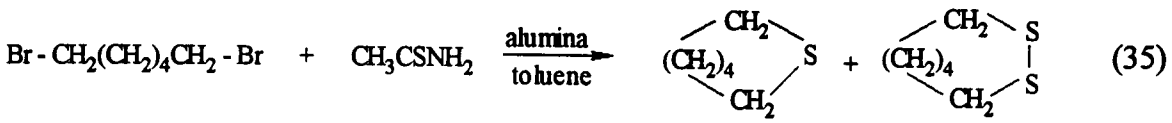
Table I-32. Synthesis of Pentamethylene Sulfide and Pentamethylene Disulfide via the Reaction of 1.0 mmol 1,5-Dibromopentane with Varying Amounts of Thioacetamide and Alumina in Refluxing Toluene.

Entry	Amount CH_3CSNH_2	Amount Al_2O_3	% Yield	
			monosulfide	disulfide
A	1.0 mmol	2.00 g	26.3	26.8
B	2.0 mmol	2.00 g	28.3	29.2
C	5.0 mmol	2.00 g	27.2	18.6
D	2.0 mmol	1.00 g	28.8	31.2
E	2.0 mmol	5.00 g	16.9	18.8
F	1.0 mmol	1.00 g	27.7	29.6

The reaction of 1,5-dibromopentane with thioacetamide and alumina turned out to be a reasonable method for synthesizing pentamethylene disulfide, in addition to producing pentamethylene sulfide.

Reaction of 1,6-Dibromohexane with Thioacetamide and Alumina.

1,6-Dibromohexane was refluxed in 10 ml of toluene containing alumina and an excess amount of thioacetamide for 10 hours, resulting in the formation of hexamethylene sulfide and disulfide (eq 35). The products were isolated by preparative gas chromatography and characterized by GC/MS and ^{1}H NMR spectroscopy. The results of the reactions are shown in Table I-33.



(35)

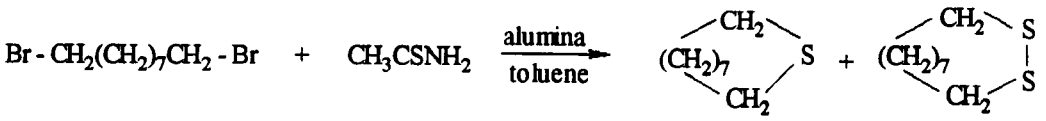
Table I-33. Synthesis of Hexamethylene Sulfide and Hexamethylene Disulfide by the Reaction of 1.0 mmol of 1,6-Dibromohexane with Varying Amounts of Thioacetamide and Alumina.

Entry	Amount of CH_3CSNH_2	Amount of Al_2O_3	% Yield	
			monosulfide	disulfide
1	1.0 mmol	1.00 g	15.9	16.6
2	1.0 mmol	2.00 g	15.2	15.8
3	2.0 mmol	1.00 g	17.9	26.3
4	2.0 mmol	2.00 g	16.8	18.2
5	5.0 mmol	2.00 g	16.3	28.4

The reaction of 1.0 mmol of 1,6-dibromohexane with 2.0 mmol of thioacetamide and 1.00 gram of alumina provided the best yields of hexamethylene sulfide and hexamethylene disulfide, 17.9% and 26.3%, respectively (Entry 3, Table I-33). The use of 5.0 mmol of thioacetamide gave a higher yield of hexamethylene disulfide compared to hexamethylene sulfide.

Reaction of 1,9-Dibromononane with Thioacetamide and Alumina.

1,9-Dibromononane (1.0 mmol) in 10 ml of refluxing toluene was treated with varying amounts of thioacetamide and alumina for 10 hours under argon (eq 36). The products, nonamethylene sulfide and disulfide, were isolated by preparative gas chromatography and characterized by GC/MS and ^1H NMR spectroscopy. The results of those reactions are tabulated in Table 34.



(36)

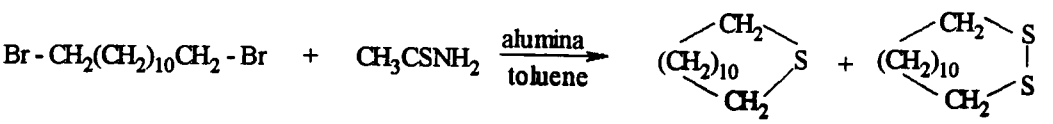
Table I-34. Synthesis of Nonamethylene Sulfide and Disulfide by the Reaction of 1.0 mmol of 1,9-Dibromononane with Varying Amounts of Thioacetamide and Alumina.

Entry	Amount CH_3CSNH_2	Amount Alumina	% Yield	
			sulfide	disulfide
1	1.0 mmol	1.00 g	5.6	12.4
2	1.0 mmol	2.00 g	6.3	12.8
3	2.0 mmol	1.00 g	8.9	16.4
4	2.0 mmol	2.00 g	8.6	15.1

It should be noted that the best yield of the organosulfides was obtained when 1.0 mmol of 1,9-dibromononane was treated with 2.0 mmol of thioacetamide and 1.0 gram of alumina (Entry 3, Table I-34).

Reaction of 1,12-Dibromododecane with Thioacetamide and Alumina.

This reaction was performed by refluxing a solution of 1.0 mmol of 1,12-dibromododecane in 10 ml of toluene containing varying amounts of thioacetamide and alumina under argon for 10 hours. This reaction afforded two products which were identified as dodecamethylene sulfide and dodecamethylene disulfide by GC/MS and ^1H NMR spectroscopy (eq 37). The results of the reactions are summarized in Table I-35.



(37)

Table I-35. Synthesis of Dodecamethylene Sulfide and Disulfide by the Reaction of 1.0 mol of 1,12-Dibromododecane with Varying Amounts of Thioacetamide and Alumina.

Entry	Amount CH_3CSNH_2	Amount Alumina	% Yield	
			sulfide	disulfide
1	1.0 mmol	1.00 g	12.2	26.3
2	1.0 mmol	2.00 g	12.8	24.4
3	2.0 mmol	1.00 g	15.2	28.4
4	2.0 mmol	2.00 g	13.1	27.9

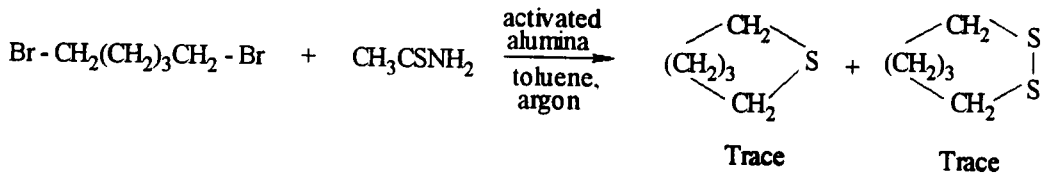
2.0 mmol of thioacetamide and 1.00 grams of alumina gave the highest product yields of the two products, dodecamethylene sulfide and disulfide, being formed in 15.2% and 28.4%, respectively (Entry 3, Table I-35).

Reaction of 1,5-Dibromopentane with Thioacetamide and Alumina Activated at 400°C.

All the reactions of 1,5-dibromopentane, 1,6-dibromohexane, 1,9-dibromononane and 1,12-dibromododecane with thioacetamide described in the previous few pages had been performed with out-of-the-bottle (unactivated) alumina. In order to see if the surface type of alumina played a role in the yields of products, alumina activated at 400°C was also used as the reacting medium. 1,5-Dibromopentane was chosen as the model compound for this study. Alumina activated at 400°C contains fewer hydroxyl groups than unactivated alumina. If the hydroxyl groups on alumina played a role in the formation of the two products, the reaction of 1,5-dibromopentane with thioacetamide and activated alumina should result in lower yields of the two products.

This reaction was performed following the procedure used for the reaction of 1,5-dibromopentane with thioacetamide described on page 69. The alumina, however, was

first dehydrated at 400°C for 4 hours using the procedure described on page 93. The reaction mixture consisting of Al_2O_3 (1 g), 1,5-dibromopentane and thioacetamide, 1.0 mmol and 2.0 mmol, respectively, was slurried in refluxing toluene (10 ml) for 10 hours under argon. GC/MS and ^1H NMR spectroscopy revealed the presence of large amounts of unreacted 1,5-dibromopentane (71.2%) and only traces of the pentamethylene sulfide and pentamethylene disulfide (eq 38).



(38)

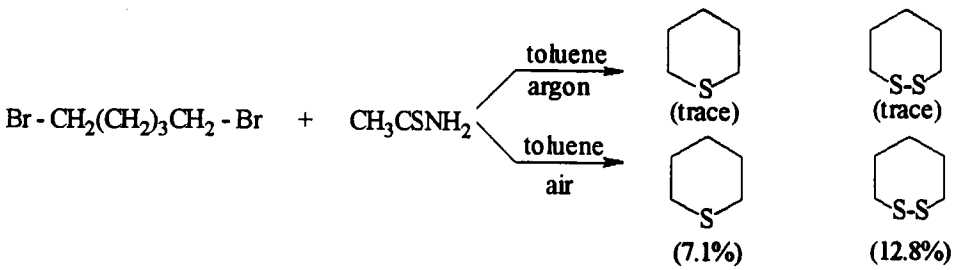
The surface of alumina clearly plays an important role in the reaction. When the alumina is dehydrated at 400°C, adjacent hydroxyl groups react to form water which is driven from the surface. Approximately 60% of the OHs are lost under these conditions.[9] The loss of the hydroxyls is the likely cause for the lower yield of cyclic sulfide and disulfide on the dehydrated alumina.

Reaction of 1,5-Dibromopentane with Thioacetamide without Alumina.

A reaction was also carried out by treating 1,5-dibromopentane with thioacetamide in the absence of alumina to study the role that alumina plays in the reaction. 1,5-Dibromopentane (1.0 mmole) dissolved in 10 ml of toluene was introduced into two separate round bottom flasks, each charged with thioacetamide (2.0 mmole). Alumina was not added in either case. One of the reaction mixtures was refluxed for 10 hours under argon, while the other was refluxed for 10 hours in air. The reaction that was run

under argon yielded only traces of pentamethylene sulfide and disulfide (Scheme I-6). The reaction that was run under air, however, yielded 7.1% of pentamethylene sulfide and 12.8% of pentamethylene disulfide. Water vapor from the air may hydrolyze thioacetamide when the reaction is run in air.

Scheme I-6. Synthesis of Pentamethylene Sulfide and Disulfide by the Reaction of 1,5-Dibromopentane with Thioacetamide.



Although the reaction of 1,5-dibromopentane and thioacetamide without alumina in air resulted in the formation of pentamethylene sulfide and disulfide, higher yields of the products were formed when the reaction was run on alumina (Entry D, Table I-32, page 70).

The results of some of the reactions of dibromoalkanes and thioacetamide with or without alumina are summarized in Table I-36.

Reaction of 1,5-dibromopentane with unactivated alumina under argon resulted in 28.3% and 31.2% of pentamethylene sulfide and pentamethylene disulfide, respectively. Running the reaction of 1,5-dibromopentane under argon in the absence of alumina, on the other hand, afforded only traces of pentamethylene disulfide and sulfide. The presence of unactivated alumina is thus necessary for the formation of the

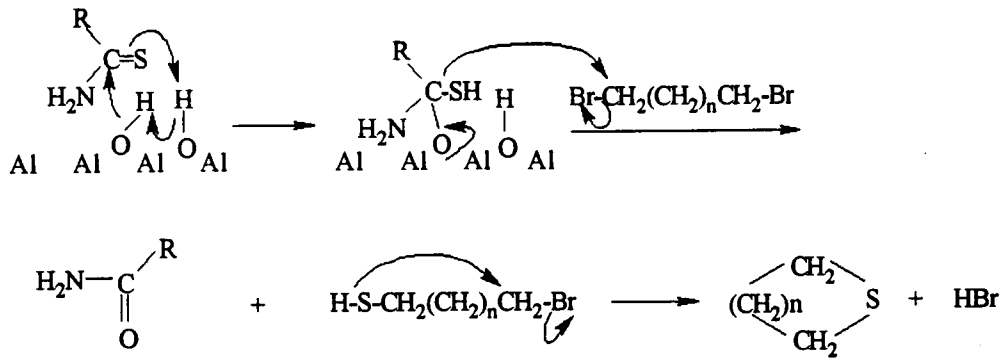
Table I-36. The Reactions of Dibromoalkanes with Thioacetamide under Various Reaction Conditions.

Dibromoalkane[a]	Reaction Conditions[b]	% yield	
		monosulfide	disulfide
1,5-Dibromopentane	CH_3CSNH_2 + Al_2O_3 (under argon)	28.3	31.2
1,6-Dibromohexane	CH_3CSNH_2 + Al_2O_3 (under argon)	17.9	26.3
1,12-Dibromodo-decane	CH_3CSNH_2 + Al_2O_3 (under argon)	15.2	28.4
1,5-Dibromopentane	CH_3CSNH_2 + dehydrated Al_2O_3 (under argon)	0	trace
1,5-Dibromopentane	CH_3CSNH_2 without Al_2O_3 (under argon)	trace	trace
1,5-Dibromopentane	CH_3CSNH_2 without Al_2O_3 (under atm. air)	7.1	12.8
1,9-Dibromononane	CH_3CSNH_2 + Al_2O_3 (under argon)	8.9	16.4
1,5-Dibromopentane	CH_3CSNH_2 + Silica gel (under argon)	25.3	26.4

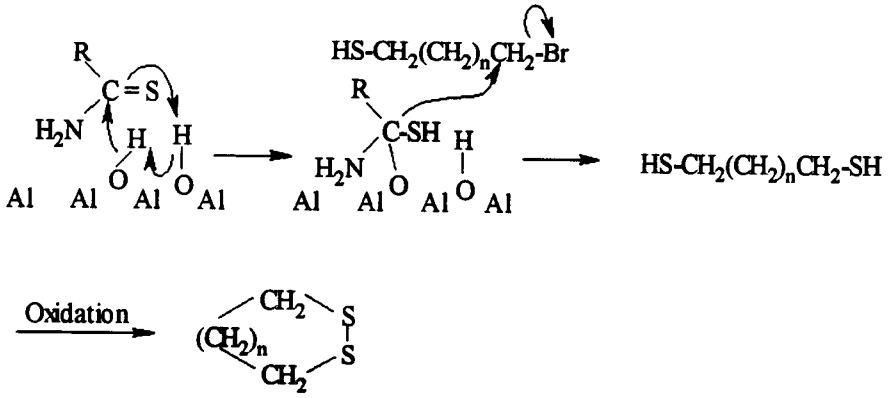
[a]Amount Dibromoalkane used = 1.0 mmol [b] Amount CH_3CSNH_3 used = 2.0 mmol, Al_2O_3 or Silica Gel = 1.0 gram

pentamethylene sulfide and disulfide in the reaction of 1,5-dibromopentane and thioacetamide. The reaction of 1,5-dibromopentane with alumina activated at 400°C under argon gave only a trace of the pentamethylene sulfide and no pentamethylene disulfide. Therefore, hydroxyl groups on alumina play a vital role in the formation of the pentamethylene sulfide and disulfide (Scheme 7).

Scheme 7. (a) Formation of Pentamethylene Sulfide in the Reaction of 1,5-Dibromopentane with Thioacetamide and Alumina.

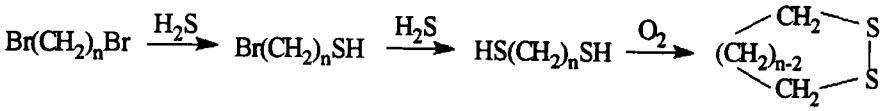


Scheme 7. (b) Formation of Pentamethylene Disulfide in the Reaction of 1,5-Dibromopentane with Thioacetamide and Alumina.



When the reaction above was run without alumina under atmospheric air, pentamethylene sulfide (7.1%) and disulfide (12.8%) were formed. In this case, the moisture in the air must have played a role in the formation of the pentamethylene sulfide and disulfide. It is reasonable to suppose that thioacetamide reacted with moisture from the air to form H_2S, which then reacted with 1,5-dibromopentane.

These reaction of thioacetamide and alumina with dibromoalkane yielded the cyclic disulfide in significant amounts in addition to the expected cyclic monosulfide (Table I-36 above). It is interesting to note that the disulfides are generated in these reactions but not when the reaction was run on S^{-2}/Al_2O_3. There is a plausible explanation for these results. The reactions that were carried out on S^{-2}/Al_2O_3 involved ions such as S^{-2} and the thiolates which remained attached to the surface. Therefore, it is not possible to liberate dithiols, which are the precursors to the disulfides, from the surface by extraction of the solid with toluene or diethyl ether. With thioacetamide, however, the chemistry involves neutral species such as H_2S and thiols. These neutral species are free to leave the surface at one place and return, and perhaps react, at another place. It is therefore possible to generate dithiols in solution, which are oxidized by O_2 during workup, to form disulfides (eq 39).



(39)

Reaction of 1,5-Dibromopentane with Thioacetamide and Silica Gel.

In addition to using alumina as the medium for the reaction of 1,5-dibromopentane and thioacetamide, the use of silica gel was also investigated. Silica gel (Figure I-11) also has a surface layer of hydroxyl groups which could aid the hydroylsis of thioacetamide, thus resulting in *in situ* formation of H_2S. A reaction between 1,5-dibromopentane and thioacetamide in the presence of silica gel was carried out as follows.

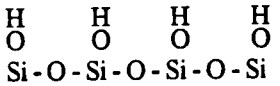
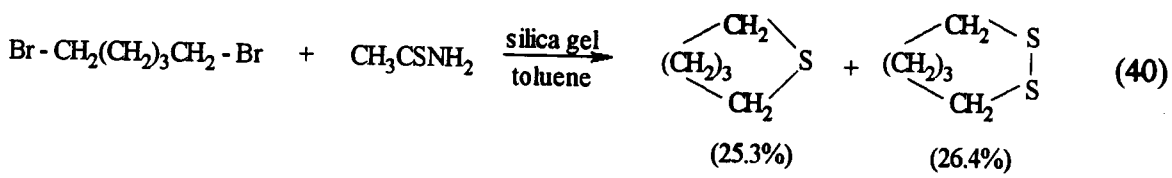


Figure I-11 Surface of Silica Gel.

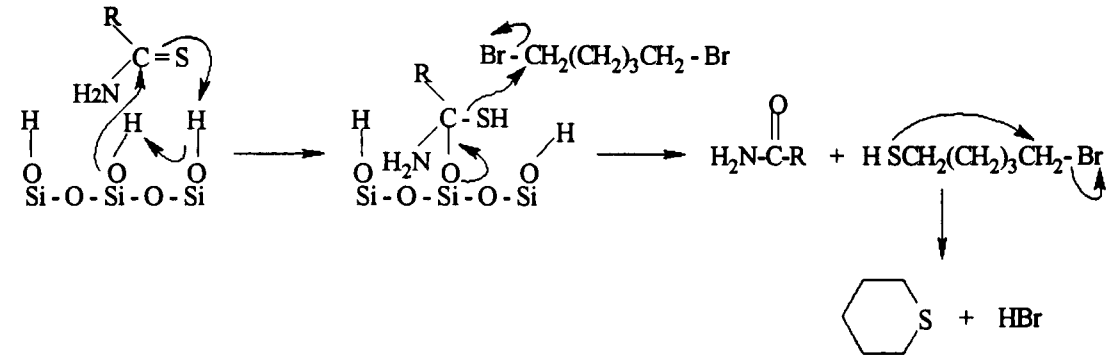
The reaction of 1,5-dibromopentane (1.0 mmol), thioacetamide (2.0 mmol) and silica gel (1.00 g) was run in 10 ml of refluxing toluene for 10 hours under argon. The products were isolated by preparative gas chromatography and characterized by ^{1}H NMR spectroscopy and GC/MS as pentamethylene sulfide and pentamethylene disulfide, formed in 25.3% and 26.4% yields, respectively (eq 40). The results are summarized in Table I-36, page 76.



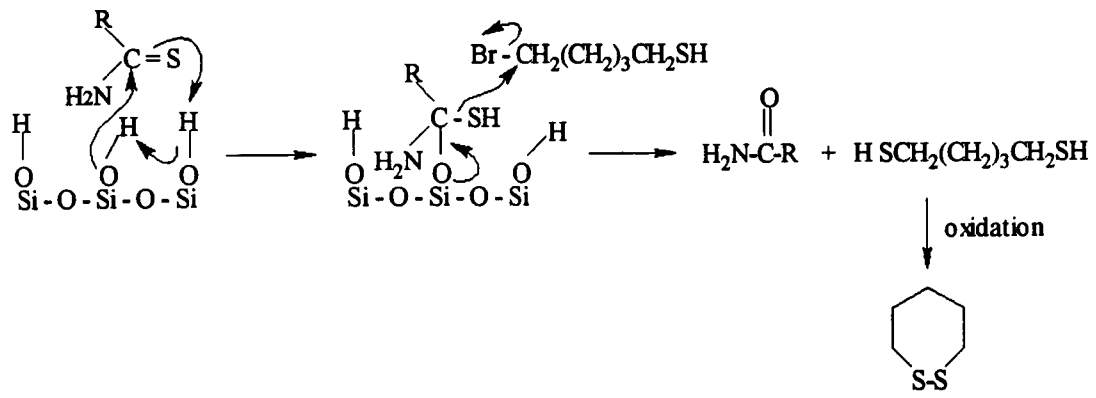
(40)

The results show that silica gel facilitates the reaction of 1,5-dibromopentane and thioacetamide to afford pentamethylene sulfide and disulfide. The surface hydroxyl groups on silica gel must have aided the hydroylsis of thioacetamide to generate H_2S. The H_2S in turn reacts with 1,5-dibromopentane to form pentamethylene sulfide and disulfide (Scheme I-8).

Scheme I-8. (a) Formation of Pentamethylene Sulfide in the Reaction of 1,5-Dibromopentane with Thioacetamide and Silica Gel.



Scheme I-8. (b) Formation of Pentamethylene Disulfide in the Reaction of 1,5-Dibromopentane with Thioacetamide and Silica Gel.



We also attempted to synthesize dialkyl sulfides and/or dialkyl disulfides by the reaction of alkyl halides with thioacetamide and alumina. The results are summarized below.

Reaction of Alkyl Halide with Thioacetamide and Alumina.

1-Iodobutane and 1-bromobutane were chosen for this study. Each alkyl halide was mixed with the thioacetamide in a 1 to 2 ratio (alkyl halide to thioacetamide) and the reactions carried out according to the procedures used for the reaction of alkyl dibromides with thioacetamide and alumina.

a. Reaction of 1-Iodobutane with Thioacetamide and Alumina.

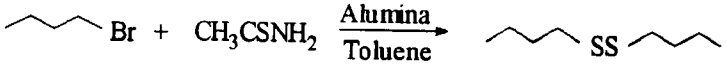
1.0 mmol of 1-iodobutane was treated with 2.0 mmol of thioacetamide and 1.00 gram of alumina in refluxing toluene for 10 hours under argon. The product was isolated by preparative gas chromatography and characterized by ^{1}H NMR spectroscopy and GC/MS identified the isolated product as di-*n*-butyl disulfide (68.9% yield) (eq 41).



(41)

b. Reaction of 1-Bromobutane with Thioacetamide and Alumina.

This reaction was run identically to the one described above for 1-iodobutane. The sole product, formed in 59.2% yield, was identified as di-*n*-butyl disulfide by ^{1}H NMR spectroscopy and GC/MS (eq 42).



(42)

The results of the reactions of the alkyl monohalides with thioacetamide and alumina described above are summarized in Table I-37.

Table I-37. The Reactions of Alkyl Monohalides with Thioacetamide and Alumina.

Alkyl Monohalide	Dialkyl Disulfide	% Yield[a]
1-Iodobutane	*n*-Dipropyl disulfide	68.9%
1-Bromobutane	*n*-Dibutyl disulfide	59.2%

[a]GC yields were calculated based on the amount of alkyl halide that had reacted.

Based on the percent yields of the respective dialkyl disulfides from the reaction of thioacetamide with 1-iodobutane and 1-bromobutane, it is fair to conclude that the iodine anion has a greater leaving group ability than bromine ($I^- > Br^-$). H_2S formed in the reaction of thioacetamide and alumina, reacted with 1-butyl halide to form $CH_3CH_2CH_2CH_2SH$, which yielded di-*n*-butyl disulfide on oxidation by O_2 during workup.

CHAPTER 6

EXPERIMENTAL SECTION

A. Materials

i. Solvents

Acetone, Mallinkrodt, ACS grade.*

Anhydrous diethyl ether, Ether, Mallinkrodt, ACS grade.*

Toluene, Aldrich Chemical Co., ACS grade.*

Cyclohexane, Aldrich Chemical Co., ACS grade.*

Absolute Ethanol, Aldrich Chemical Co., ACS grade.*

Acetonitrile, Fisher.*

ii. Gases

Argon, Ar, MG Industries, was used without further purification.

iii. Reagents

Benzyl bromide, Aldrich Chemical Co.*

1-Bromooctane, Aldrich Chemical Co.*

1-Bromobutane, Aldrich Chemical Co.*

1,2-Dibromoethane, Aldrich Chemical Co.*

1,3-Dibromopropane, Aldrich Chemical Co.*

1,4-Dibromobutane, Aldrich Chemical Co.*

1,5-Dibromopentane, Aldrich Chemical Co.*

1,6-Dibromohexane, Aldrich Chemical Co.*

1,7-Dibromoheptane, Aldrich Chemical Co.*

1,8-Dibromooctane, Aldrich Chemical Co.*

1,9-Dibromononane, Aldrich Chemical Co.*

1,10-Dibromodecane, Aldrich Chemical Co.*

1,12-Dibromododecane, Aldrich Chemical Co.*

1,16-Dibromohexadecane, Pfaltz and Bauer.*

Sodium sulfide nonahydrate, Aldrich Chemical Co.*

Sodium fluoride, Aldrich Chemical Co.*

Bis(tri-*n*-butyltin)sulfide, Pfaltz and Bauer.*

Thioacetamide, Aldrich Chemical Co., ACS grade.*

Decane, Aldrich Chemical Co., ACS grade.*

Nonane, Aldrich Chemical Co., ACS grade.*

Undecane, Aldrich Chemical Co., ACS grade.*

Nitromethane, Aldrich Chemical Co., ACS grade.*

Alumina, Brockmann Activity 1, Aldrich Chemical Co.*

Activated/Dehydrated Alumina Brockmann Activity 1, Aldrich Chemical Co., activated alumina was prepared by activating Brockman Activity Grade 1 alumina using the method and appartus described by Pagni, Kabalka, *et al.*[21]

* chemical was used without purification.

B. Experimental Methods

i. Physical Properties and Analytical Methods

Preparative gas chromatography was performed using a Varian 3300 gas chromatograph equipped with 6' x 1/4" 20% SE-30 on Chromasorb W column. Gas chromatography was performed on a Hewlett-Packard 5890A GC instrument equipped with a 30 m x 1/8" column packed with 30% SE-30 by weight on Chromosorb W as the solid support. Gas chromatograph/Mass spectrometry (GC/MS) was performed using a Hewlettt-Packard 5970 Gas chromatograph/Mass spectrometer detector. Nuclear magnetic resonance spectra were recorded either on a 90 MHz JEOL FX-90Q spectrometer or a BRUCKER 250 MHz spectrometer, and the chemical shifts (in parts per million) were reported in reference to tetramethylsilane (TMS) with $\delta = 0$ ppm. All of the samples were dissolved in deuterated chloroform.

ii. Manipulation of S^{-2}/Al_2O_3

Due to the possibility of readsorption of H_2O from the atmosphere onto the S^{-2}/Al_2O_3 complex after it is prepared, the S^{-2}/Al_2O_3 complex was stored under argon immediately after it was prepared. Transfer of S^{-2}/Al_2O_3 was done with minimal exposure to the air. All glasswares and stirbars use were oven-dried before use. The reactions were performed under a slight positive pressure of argon using a pressure-regulated argon source with a mercury bubbler.

C. Experimental Procedures

i. Preparation of S^{-2}/Al_3O_3 complex

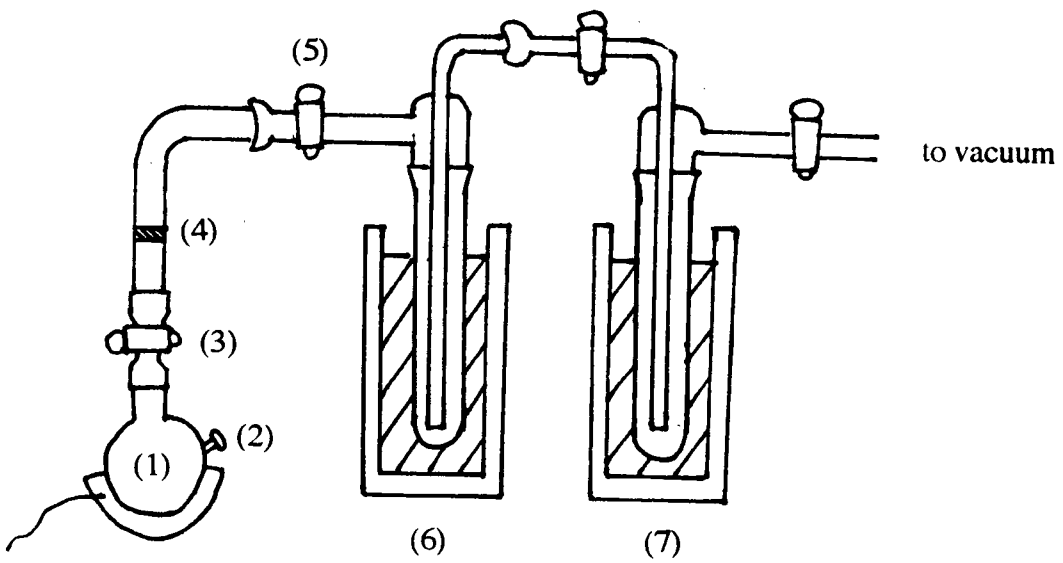
A 200 ml round bottom flask was charged with a solution of sodium sulfide nonahydrate (40.0 g, 16.6 mmol), in a minimal amount of distilled water (~45 ml) and neutral alumina (20.0 g, Brockmann activity 1). The mixture was stirred for 20 minutes using a magnetic stirbar and a magnetic stirrer under argon. The stirbar was then removed from the flask and the flask transferred to a rotary evaporator and water removed under reduced pressure, keeping the bath temperature below 80°C. The resulting free flowing reagent was then dehydrated by heating under vacuum ($\leq$ 0.5 mm Hg) for 1½ hours at either 95°C or 110°C utilizing the apparatus designed by Pagni, Kabalka, *et al.*[21]

(a) Vacuum System Designed by Pagni, Kabalka, et. al.[21]

The system used for the activation/dehydration of alumina is shown below. This system utilizes a vacuum apparatus with two traps (6) and (7). The water removed from the alumina is collected in trap (6). Trap (7) is used as protection for the vacuum pump to avoid contamination that could damage the pump itself. A valve (5) is connected to trap (6) to allow the release of the vacuum when necessary. The system is also equipped with a glass frit (4), which prevents the solid being activated from being pulled into the vacuum pump. A removable valve (3) is attached to allow for the closure of the round bottom flask (1) when necessary. The septum was found to withstand the high vacuum

and temperature quite well. This septum was not used in the present studies. The septum can be used for introduction of reagents to the solid if needed.

The flask is connected to the vacuum system and the entire system is evacuated to 0.005 millimeters of Hg. The alumina in the round bottom flask is then heated to the appropriate temperature and the water vapor that evolved is collected in trap (6) by cooling the trap in liquid nitrogen. After heating (dehydrating) the alumina for an appropriate period of time, the heating mantle is removed and the dehydrated alumina is allowed to cool. The round bottom flask is then closed off from the rest of the system using valve (3). The closed flask can then be removed from the vacuum system and the activated solid can be stored in an air-tight container under argon.



Calculations to determine the number of moles of sulfide adsorbed per gram of solid and per gram of alumina for the above reagent are described on page 16 in the Results and Discussion Section.

ii. Formation of Dialkyl Sulfide. General Procedure.

(a) Reaction of Benzyl Bromide with the S^{-2}/Al_2O_3. General Procedure A.

Benzyl bromide (0.25 g, 1.5 mmol) was dissolved in cyclohexane (10 ml) in a 100 ml round bottom flask. To this was added 0.58 g of 3.80 x 10^{-3} mol S^{-2}/g solid complex and the resulting mixture stirred for 20 hours at 80°C under argon. After cooling, the liquid and solids were separated. The solid was then stirred with three 35 ml portions of anhydrous diethyl ether and filtered by gravity filtration through a piece of fine grain filter paper. The anhydrous diethyl ether and cyclohexane were combined and were removed by evaporating at 65°C on a rotoevaporator. The residual yellowish colored oily liquid consisting largely of dibenzyl sulfide was recrystallized from 70% ethanol; m.p. 49°: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 3.56 (s, 4H, $(C_6H_5\underline{CH_2})_2S$), 7.24 (s, 10H, $(\underline{C_6H_5}CH_2)_2S$); lit.[20] 3.46, 7.17); MS, cal'd for $C_{14}H_{14}S$ m/z 214.3, found m/z 214. The product also has a GC retention time and MS identical to the known compound. Dibenzyl sulfide was formed in 58.6% yield.

(b) Reaction of Benzyl Chloride with the S^{-2}/Al_2O_3 Complex.

To a solution of benzyl chloride (0.25 g, 2.0 mmol) in 10 ml of cyclohexane in a 100 ml round bottom flask was added 0.73 g of S^{-2}/solid (3.80 x 10^{-3} mol S^{-2}/g solid)

complex. The reaction mixture was stirred for 20 hours at 90°C under argon and, after cooling, the product mixture was extracted with three 35 ml portion of anhydrous diethyl ether. After removing the solid by filtration through filter paper, the anhydrous diethyl ether and cyclohexane were removed in vacuo at 65°C using a rotoevaporator. The residual yellowish colored oil was then place in an ice bath until it solidified and the product was recrystallized from 70% ethanol; m.p. 49°: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 3.56 (s, 4H, $(C_6H_5\underline{CH_2})_2S$), 7.24 (s, 10H, $(\underline{C_6H_5}CH_2)_2S$); (lit.[20] 3.46, 7.17); MS, cal'd for $C_{14}H_{14}S$ m/z 214.3, found m/z 214. Dibenzyl sulfide was formed in 56.6% yield.

(c) Reaction of 1-Bromobutane with the S^{-2}/Al_2O_3 Complex.

As with the reaction of benzyl bromide with S^{-2}/Al_2O_3 above, 1-bromobutane (0.25 g, 1.83 mmol) in 10 ml of cyclohexane and 6.09 x 10^{-4} mol S^{-2}/g solid complex (3.00 g of S^{-2}/solid, 6.09 x 10^{-4} mol S^{-2}) gave 48.0% of di-*n*-butyl sulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 0.97 (6H, CH_3), 1.50 (m, 8H, $(CH_3(\underline{CH_2})_2CH_2)_2S$), 2.50 (4H, $(CH_3(CH_2)_2\underline{CH_2})_2S$); (lit[20] 0.98, 1.50, 2.50); MS cal'd for $C_8H_{18}S$ m/z 146.3, found m/z 146.

(d) Reaction of 1-bromooctane with the S^{-2}/Al_2O_3 Complex.

As with dibenzyl sulfide synthesis above (page 88), 1-bromooctane (0.50 g, 2.59 mmol) in 10 ml cyclohexane and 3.80 x 10^{-3} mol S^{-2}/g solid complex (1.00 g, 3.80 x 10^{-3} mol S^{-2}) gave 43.2% of di-*n*-octyl sulfide as a colorless liquid: ^{1}H NMR (90 MHz,

$CDCl_3$) δ: 0.89 (6H, m, $\underline{CH_3}(CH_2)_6CH_2$-S-$CH_2(CH_2)_6\underline{CH_3}$), 1.30 (24H, m, $CH_3(\underline{CH_2})_6CH_2SCH_2(\underline{CH_2})_6CH_3$), 2.43 (4H, m, $CH_3(CH_2)_6\underline{CH_2}S\underline{CH_2}(CH_2)_6CH_3$); (lit.[20] 0.89, 1.30, 2.42) MS cal'd for $C_{16}H_{34}S$ m/z 258.3, found m/z 258.

(e) Reaction of 1-Iodoethane with the S^{-2}/Al_2O_3 Complex.

As with dibenzyl sulfide synthesis above (page 88), 1-iodoethane (0.50 g, 3.21 mmol) in 10 ml of cyclohexane and 4.81 x 10^{-3} mol S^{-2}/g solid complex (0.83 g, 4.00 x 10^{-3} mol S^{-2}) gave 21.0% of diethyl sulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.17- 1.33 (6H, t, $\underline{CH_3}CH_2)_2S$), 2.42 - 2.66 (4H, q, $(CH_3\underline{CH_2})_2S$); (lit[20]. 1.17-1.32, 2.42-2.65) MS cal'd for $C_4H_{10}S$ m/z 90.2, found m/z 90.

iii. Formation of Cyclic Sulfides Using the Procedure of Mandolini *et al.*[8]

A Representative Procedure.

(a) Reaction of 1,7-Dibromoheptane with $Na_2S\bullet 9H_2O$ in HMPT.

The reaction was run in a 250 ml three-necked flask equipped with a magnetic stir bar, charged with 20 ml of HMPT. The central neck was fitted with a reflux condenser and the two side necks with two 50 ml glass syringes with the syringe needles dipping into the solvent heated at 55°C. The reagents were added dropwise, separately and simultaneously, to the well-stirred solvent. One syringe contained 0.50 grams (1.9 mmol) of the 1,7-dibromoheptane in 5 ml of MeOH, and the other contained 0.46 grams (1.9 mmol) of $Na_2S\cdot 9H_2O$ in the same amount of MeOH. The addition took 20 minutes, after which the heating was continued for an additional 10 minutes. Water (40 ml) was

then added, and the mixture continuosly extracted with pentane for 2 hours. The pentane extracts were washed with water, dried with Na_2SO_4 and evaporated in vacuo at 50°C. The crude sulfide was eluted on silica gel with $CHCl_3$/petroleum ether (1:9) to remove impurities. The product, heptamethylene sulfide, was isolated by preparative gas chromatography; 58.1%: mp 34 - 37°C (lit.[8] mp 33 - 34°C); ^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.25 - 1.80 (m, 10H, $(\underline{CH_2})_5$), 2.35 - 2.65 (t, 4H, $\underline{CH_2}S$); (lit. 1.25 - 1.80, 2.65); MS cal'd for $C_7H_{14}S$ m/z 130.2, found (M-1) 129.

(b) Reaction of 1,8-Dibromooctane with $Na_2S \bullet 9H_2O$ in HMPT. (Procedure by Mandolini et al.[8])

As with the synthesis of heptamethylene sulfide by the method of Mandolini *et al.*[8] above, 1,8-dibromooctane (0.27g, 1.0 mmol) in 3 ml MeOH and 0.24g (1.0 mmol) $Na_2S \cdot 9H_2O$ in 3 ml MeOH gave 39.3 % of octamethylene sulfide: mp 39-40°C; ^{1}H NMR (250 MHz) δ: 1.20-2.80 (m, 12H, $(\underline{CH_2})_6$), 2.30-2.55 (t, 4H, $\underline{CH_2}S$); MS cal'd for $C_8H_{16}S$ m/z 144.3, found m/z 144.

c) Reaction of 1,9-Dibromononane with $Na_2S \cdot 9H_2O$ in HMPT. (Procedure by Mandolini et al.[8])

As with the synthesis of heptamethylene sulfide by the method of Mandolini *et al.*[8] above, 1,9-dibromononane (0.29g, 1.0 mmol) in 3 ml MeOH and 0.24g (1.0 mmol) $Na_2S \cdot 9H_2O$ in 3 ml MeOH gave 22.0 % of nonamethylene sulfide: mp 39-41°C; (lit[8] mp.

38-39°C); ^{1}H NMR (250 MHz) δ: 1.20-1.79 (14H, m, $(\underline{CH_2})_7$), 2.40-2.64 (t, 4H, $\underline{CH_2}S$); MS cal'd for $C_9H_{18}S$ m/z 158.3, found m/z 158.

iv. Formation of Cyclic Sulfides Using S^{-2}/Al_2O_3 Complexes. General Procedure.

(a) Reaction of 1,5-Dibromopentane with the S^{-2}/Al_2O_3Complex. General Procedure B.

To a 100 ml round bottom flask was added a solution of 1,5-dibromopentane (0.50 g, 2.17 mmol) in 10 ml of toluene and 1.45 g of S^{-2}/solid (2.42×10^{-3} mol S^{-2}/g solid) complex. The reaction mixture was stirred at 90°C for 20 hours under argon and, after cooling to room temperature, the product mixture was extracted with three 35 ml portions of anhydrous diethyl ether. After removing the solid by filtration through filter paper, the anhydrous diethyl ether and toluene were removed in vacuo at 65°C using a rotoevaporator. The product, pentamethylene sulfide, was isolated by preparative gas chromatography; 68.5%: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.3 - 2.1 (m, $(\underline{CH_2})_3$, 6H), 2.59 (t, 4H, $\underline{CH_2}S$) (lit.[20] 1.30-2.10, 2.58); MS cal'd for $C_5H_{10}S$ m/z 102.2, found m/z 102.

(b) Reaction of α,α'-Dibromo-o-xylene with the S^{-2}/Al_2O_3 Complex.

As with the synthesis of pentamethylene sulfide above, α,α'-dibromo-o-xylene (0.50 g, 1.9 mmol) in 10 ml of toluene and 2.42×10^{-3} mol S^{-2}/g solid complex (1.27 g, 3.07 mmol S^{-2}) gave 68.2% of 1,3-dihydroisothianaphene, a light brown liquid that darkened rapidly: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 4.22 (s, 4H, $\underline{CH_2}$), 7.2 (s, 4H, $\underline{C_6H_5}$); (lit.[19] 4.06, 7.02 in CCl_4); MS cal'd for C_8H_8S m/z 136.2, found m/z 136.

(c) Reaction of 1,4-Dibromobutane with the S^{-2}/Al_2O_3 Complex.

As with the synthesis of pentamethylene sulfide discussed above, 1,4-dibromobutane (0.50 g, 2.32 mmol) in 10 ml of toluene and 0.59 g of 4.85 x 10^{-3} mol S^{-2}/g solid complex gave 0.091 g (44.7%) of tetrahydrothiophene: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.30 - 2.11 (m, 4H, $\underline{CH_2}$), 2.58 (t, 4H, $\underline{CH_2}S$); (lit.[19] 1.30- 2.10, 2.59); MS cal'd for C_4H_8S m/z 88.2, found m/z 88.

(d) Reaction of 1,6-Dibromohexane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the pentamethylene sulfide synthesis above, 1,6-dibromoheptane (0.50 g, 2.05 mmol) dissolved in 10 ml of toluene and 2.44 g of 1.49 x 10^{-3} mol S^{-2}/g solid (3.64 mmol S^{-2}) (activated at 95°C) gave 62.4% of hexamethylene sulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.50 - 1.90 (m, 8H, $(\underline{CH_2})_4$), 2.55 - 2.85 (t, 4H, $\underline{CH_2}S$) (lit.[19] 1.50 - 1.90, 2.55 - 2.85); MS cal'd for $C_6H_{12}S$ m/z 116.2, found m/z 116.

(e) Reaction of 1,8-Dibromooctane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the synthesis of pentamethylene sulfide described above, 1,8-dibromooctane (0.27 g, 1.0 mmol) in 10 ml of toluene and 3.14 g of 6.02 x 10^{-4} mol S^{-2}/g solid (activated at 95°C) gave 37.7% of octamethylene sulfide: mp 38 - 41°C (lit.[8] mp 36 - 37°C); ^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.20 - 2.79 (m, 12H, $(\underline{CH_2})_6$), 2.31 - 2.56 (t, 4H, $\underline{CH_2}S$); (lit.[8] 1.20 - 2.80, 2.30 - 2.55); MS cal'd for $C_8H_{16}S$ m/z 144.3, found (M-1) 143.

(f) Reaction of 1,9-Dibromononane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the pentamethylene sulfide described above, 1,9-dibromononane (0.29 g, 1.0 mmol) dissolved in 10 ml toluene and 3.21 g of 6.02 x 10^{-4} mol S^{-2}/g solid (activated at 95°C) gave 15.7% of nonamethylene sulfide: mp 39 - 42°C (lit.[8] mp 38 - 39°C); ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.20 - 1.79 (m, 14H, $(\underline{CH_2})_9$) 2.40 - 2.65 (t, 4H, $\underline{CH_2}S$); MS cal'd for $C_9H_{18}S$ m/z 158.3, found m/z 158.

(g) Reaction of 1,3-Dibromopropane with the S^{-2}/Al_2O_3 Complex.

To a solution of 1,3-dibromopropane (0.50 g, 2.5 mmol) dissolved in 10 ml of toluene in a tube was added 4.85 x 10^{-3} mol S^{-2}/g solid (110°C) (0.63 g) complex. After sealing the tube, the reaction mixture was slurried using a magnetic stirbar and magnetic stirrer for 20 hours at 140°C. After cooling to room temperature, the tube was opened and the product mixture was extracted with three 35 ml portions of anhydrous diethyl ether and the solid was removed by filtration through filter paper. The anhydrous diethyl ether and toluene were then removed in vacuo at 65°C using a rotovap. The product, trimethylene sulfide,formed in 9.3% yield, was characterized by ^{1}H NMR and GC/MS: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 3.00 (m, 2H, $\underline{CH_2}$), 3.23 (4H, $(\underline{CH_2})_2S$) [lit.[8] 3.00 (m, 2H) 3.23 (4H)]; MS cal'd for C_3H_6S m/z 74.1, found m/z 74.

(h) Reaction of 1,2-Dibromoethane with the S^{-2}/Al_2O_3 Complex.

As with the trimethylene sulfide synthesis described above, 1,2-dibromoethane (0.50 g, 2.66 mmol) in 10 ml toluene and 0.68 g of 4.85 x 10^{-3} mol S^{-2}/g solid (3.30

mmol S^{-2}) complex was slurried in a sealed tube using a magnetic stirbar and stirrer for 20 hours at 140°C. The products, ethylene sulfide and 1,4-dithiane, were collected by preparative GC and characterized by GC/MS and ^1H NMR analysis. The GC yields were 1.5% for ethylene sulfide and 1.8% for 1,4-dithiane. ^1H NMR analysis for ethylene sulfide: (90 MHz, $CDCl_3$) δ: 2.35 (s, 4H); (lit.[8,20] 2.35); MS cal'd for C_2H_4S m/z 60.1, found m/z 60. ^1H NMR analysis for 1,4-dithiane: (90 MHz, $CDCl_3$) δ: 2.84 (s, 8H); (lit.[20] 2.85); MS cal'd for $C_4H_8S_2$ m/z 120.2, found m/z 120.

(i) Reaction of 1,7-Dibromoheptane with the S^{-2}/Al_2O_3 Complex (95°C).

To a 100 ml round bottom flask was added a solution of 1,7-dibromoheptane (0.50 g, 1.9 mmol) in a 10 ml toluene and 2.31 g of 1.49 x 10^{-3} mol S^{-2}/g solid complex activated at 95°C. The reaction mixture was slurried at 90°C for 20 hours under argon and, after cooling to room temperature, the product mixture was extracted with three 35 ml portions of anhydrous diethyl ether. After removing the solid by filtration through filter paper, the anhydrous diethyl ether and toluene were removed in vacuo at 65°C using a rotoevaporator. The product, heptamethylene sulfide, was isolated by preparative gas chromatography: 47.1%; mp 34 - 37°C (lit.[8] mp 33 - 34°C); ^1H NMR (200 MHz, $CDCl_3$) δ: 1.25 - 1.80 (m, 10H, $(\underline{CH_2})_5$), 2.35 - 2.65 (t, 4H, $(\underline{CH_2})_2S$); (lit.[20] 1.25 - 1.80, 2.65); MS cal'd for $C_7H_{14}S$ m/z 130.2, found (M-1) 129.

(j) Reaction of 1,5-Dibromopentane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the synthesis of heptamethylene sulfide described above, 1,5-dibromopentane (0.50 g, 2.17 mmol) dissolved in a 10 ml toluene was slurried with 2.57 g of 1.49 x 10^{-3} mol S^{-2}/g solid (95°C). Pentamethylene sulfide was formed in 79.2% yield. ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.30 - 2.10 (m, 6H, $(\underline{CH_2})_3$), 2.59 (t, 4H, $(\underline{CH_2})_2S$); (lit.[20] 1.30 - 2.10, 2.58); MS cal'd for $C_5H_{10}S$ m/z 102.2, found m/z 102.

(k) Reaction of 1,10-Dibromodecane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the synthesis of heptamethylene sulfide described above, 1,10-dibromodecane (0.50 g, 1.67 mmol) dissolved in 10 ml toluene was slurried with 5.27 g of 6.02 x 10^{-4} mol S^{-2}/solid, activated at 95°C. Decamethylene sulfide was synthesized in 12.4% yield: mp 41 - 43°C (lit.[8] 39-40°C); ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.33 - 1.59 (m, 16H, $(\underline{CH_2})_8$), 2.17 - 2.51 (t, 4H, $(\underline{CH_2})_2S$); MS cal'd for $C_{10}H_{20}S$ m/z 172.3, found (M-1) 171.

(l) Reaction of 1,12-Dibromododecane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the reaction of heptamethylene sulfide described above, 1,12-dibromododecane (0.50 g, 1.52 mmol) dissolved in 10 ml of toluene was slurried with 4.82 g of 6.02 x 10^{-4} mol S^{-2}/g solid, activated at 95°C. Dodecamethylene sulfide was synthesized in 20.4% yield: mp 66 - 68°C (lit.[8] mp 65.5 - 66°C); ^{1}H NMR (90 MHz, $CDCl_3$) δ: 2.54 (t, 4H, $(\underline{CH_2})_2S$), 1.36 - 1.62 (m, 20H, $(\underline{CH_2})_{10}$); MS, calc'd for $C_{12}H_{24}S$ m/z 200.2, found m/z 200.

(m) Reaction of 1,16-Dibromohexadecane with the S^{-2}/Al_2O_3 Complex (95°C).

As with the reaction of heptamethylene sulfide described above, 1,16-dibromohexadecane (0.50 g, 1.30 mmol) dissolved in 10 ml toluene was slurried with 4.12 g of 6.02 x 10^{-4} mol S^{-2}/g solid, activated at 95°C. Hexamethylene sulfide was synthesized in 28.6% yield: mp 78 - 81°C; (lit. mp.); ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.25 - 1.60 (m, 28H, $(\underline{CH_2})_{14}$), 2.50 (t, 4H, $(\underline{CH_2})_2S$); MS, calc'd for $C_{16}H_{32}S$ m/z 256.5, found m/z 256.

v. Preparation of the F^-/Al_2O_3 Complex by Impregnation of NaF on Al_2O_3

To a solution of sodium fluoride (40.0g) dissolved in minimum amount of distilled water (~ 45 ml) in a 250 ml round bottom flask was added neutral alumina (10.0 g; Brockmann activity 1) in one portion. The mixture was stirred under a positive flow of argon for 20 minutes using a magnetic stirbar and a magnetic stirrer. The stir bar was removed from the flask and the flask was then transferred to a rotary evaporator and water was removed under reduced pressure, keeping the bath temperature below 65°C. The resulting reagent was then dehydrated by heating under vacuum (< 0.5 mm Hg) for 1 ½ hours at 100°C utilizing the apparatus designed by Pagni, Kabalka, *et al.*[21] The resulting F^-/solid complex was stored in an air-tight jar under argon. Calculations to determine the number of moles of fluoride adsorbed on each gram of alumina for the F^-/solid are described below.

If the reagent used consisted of 40.0 g of anhydrous NaF and 10.0 g of alumina (Brockmann Activity 1), then the number of moles of fluoride per gram of alumina in this case is 2.14 x 10^{-2} mol F^-/g Solid. This number is derived in the following way:

$$40.0\ g\ NaF\ x\ \frac{1\ mol\ NaF}{41.988\ g\ NaF} = 0.953\ mol\ NaF$$

The total weight of the alumina/fluoride complex after dehydration was 44.5 grams. Therefore, the number of moles F^- per gram of solid is:

$$\frac{0.953\ mol\ NaF}{44.5\ g\ Al_2O_3} = 2.14\ x\ 10^{-2}\ mol\ F^-/g\ solid$$

(a) Reaction of 1,5-Dibromopentane with Bis(tri-n-butyltin)sulfide on F^-/Al_2O_3 Complex.

To a solution 1,5-dibromopentane (0.1 mmol) dissolved in acetonitrile (100ml) in a 50 ml round bottom flask was added 2.0 grams of 2.14 x 10^{-2} mol F^-/g Al_2O_3 complex and then immediately followed by dropwise injection of *bis*(tri-*n*-butyltin)sulfide (0.061 g, 0.1 mmol) using a glass syringe. The injection of *bis*(tri-*n*-butyltin)sulfide was done over a period of 1 minute. The reaction mixture was stirred under a positive flow of argon at 48°C for 24 hours.

After 24 hours, the reaction was filtered and extracted with anhydrous ether. The ether and acetonitrile were removed in vacuo using a rotary evaporator. The product was transferred to a vial and 0.014 g of decane was added as the internal standard to

determine the product yield by gas chromatography following the procedure used in the reaction of 1,4-dibromobutane described above. GC analysis revealed 5% of pentamethylene sulfide.

vi. Reaction of Alkyl Dihalides and Thioacetamide with and without Alumina.

(a) Reaction of 1,5-Dibromopentane with Thioacetamide on Alumina.

General Procedure C.

To a mixture of 1,5-dibromopentane (0.23 g, 1.0 mmol) dissolved in 15 ml of toluene and 1.00 gram of unactivated alumina (Brockmann Activity Grade 1) in a 100 ml round bottom flask was added 1.23 g (2.0 mmol) of thioacetamide. The reaction mixture was slurried under argon in refluxing toluene for 10 hours. After cooling to room temperature, the solid was extracted with three 35 ml portions of anhydrous diethyl ether. After removing the solid by filtration through filter paper, the anhydrous diethyl ether and toluene were removed in vacuo at 65°C on a rotoevaporator. The products, pentamethylene sulfide and pentamethylene disulfide, were separated by preparative gas chromatography and characterized by GC/MS and NMR analysis. The reaction yielded 28.8% of pentamethylene sulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.31 - 2.11 (m, 6H, $(\underline{CH_2})_3$), 2.59 (t, 4H, $(\underline{CH_2})_2S$). (lit.[19,20] 1.30 - 2.10, 2.58); MS, calc'd for $C_5H_{10}S$ m/z 102.2, found m/z 102; and 31.2% of pentamethylene disulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.29 - 2.10 (m, 6H, $(\underline{CH_2})_3$), 2.58 (t, 4H, $(\underline{CH_2})_2S$); MS, calc'd for $C_5H_{10}S_2$ m/z 134.3, found m/z 134.

(b) Reaction of 1,6-Dibromohexane with Thioacetamide on Alumina.

As with the reaction of 1,5-dibromopentane with thioacetamide on alumina described above, the reaction of 1,6-dibromohexane (0.24 g, 1.0 mmol) dissolved in 15 ml of toluene, 1.00 gram of unactivated alumina and 1.23 g (2.0 mmol) of thioacetamide gave 0.021 g (17.9%) of hexamethylene sulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.49 - 1.98 (m, 8H, $(\underline{CH_2})_4$), 2.54 - 2.84 (t, 4H, $(\underline{CH_2})_2S$). (lit.[19,20] 1.50 - 1.90, 2.55 - 2.85); MS, calc'd for $C_6H_{12}S$ m/z 116.2, found m/z 116; and 0.039 g (26.3%) of hexamethylene disulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 1.49 - 1.8 (m, 8H, $(\underline{CH_2})_4$), 2.54 - 2.86 (t, 4H, $(\underline{CH_2})_2S$). (lit.[19,20] 1.48 - 1.80, 2.53 - 2.84); MS, calc'd for $C_6H_{12}S_2$ m/z 148.3, found m/z 148.

(c) Reaction of 1,9-Dibromononane with Thioacetamide on Alumina

As with the reaction of 1,5-dibromopentane with thioacetamide on alumina described above, the reaction of 1,9-dibromononane (0.29 g, 1.0 mmol) dissolved in 15 ml of toluene, 1.00 gram of unactivated alumina and 1.23 g (2.0 mmol) of thioacetamide gave 0.014 g (8.9%) of nonamethylene sulfide: ^{1}H NMR (250 MHz, $CDCl_3$) δ: 1.21 - 1.77 (m, 14H, $(\underline{CH_2})_7$), 2.31 - 2.63 (t, 4H, $(\underline{CH_2})_2S$) (lit.[19,20] 1.20 - 1.78, 2.40 - 2.65); MS, calc'd for $C_9H_{18}S$ m/z 158.3, found m/z 158; 0.031 g (16.4%) of nonamethylene disulfide: ^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.19 - 1.75 (m, 16H, $(\underline{CH_2})_8$), 2.39 - 2.60 (t, 4H, $(\underline{CH_2})_2S$). (lit.[19,20] 1.18 - 1.75, 2.38 - 2.60); MS, calc'd for $C_9H_{18}S_2$ m/z 190.4, found m/z 190.

(d) Reaction of 1,12-Dibromododecane with Thioacetamide on Alumina

As with the reaction of 1,5-dibromopentane with thioacetamide on alumina mentioned above, the reaction of 1,12-dibromododecane (0.328 g, 1.0 mmol) dissolved in 15 ml of toluene, 1.00 gram of unactivated alumina and 1.23 g (2.0 mmol) of thioacetamide gave 0.030 g (15.2%) of dodecamethylene sulfide: ^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.54 (t, 4H, $(\underline{CH_2})_2S$), 1.36 - 1.61 (m, 20H, $(CH_2)_{10}$). (lit.[19,20] 2.54, 1.36 - 1.62); MS, calc'd for $C_{12}H_{24}S$ m/z 200.2, found m/z 200; and 0.066 g (28.4%) of dodecamethylene disulfide: ^{1}H NMR (200 MHz, $CDCl_3$) δ: 2.51 (t, 4H, $(\underline{CH_2})_2S$), 1.30 - 1.56 (m, 20H, $(\underline{CH_2})_{10}$) (lit.[19,20] 2.51, 1.30 - 1.57); MS, calc'd for $C_{12}H_{24}S_2$ m/z 232.2, found m/z 232.

(e) Reaction of 1,5-Dibromopentane with Thioacetamide on Activated Alumina

To a 100 ml round bottom flask was added 1.00 gram of alumina (activated at 400°C for 4 hours) 0.23 g (1.0 mmol) of 1,5-dibromopentane dissolved in 15 ml of toluene and 1.23 g (2.0 mmol) of thioacetamide. The reaction mixture was slurried, worked up, and analyzed according to the procedure described for the reaction of 1,5-dibromopentane with thioacetamide on unactivated alumina (p. 99). Only traces of pentamethylene sulfide and pentamethylene disulfide were detected by GC. The yields of pentamethylene sulfide and pentamethylene disulfide were each less than 1%.

(f) Reaction of 1,5-Dibromopentane with Thioacetamide without Alumina in Air.

To 1,5-dibromopentane (0.23 g, 1.0 mmol) dissolved in 15 ml of toluene was added to 1.23 g (2.0 mmol) of thioacetamide in a 100 ml round bottom flask. No alumina was used in this reaction. The reaction mixture was slurried, worked up and analyzed according to the procedure described for the reaction of 1,5-dibromopentane with thioacetamide on alumina (page 99). The product mixture contained two products identified as pentamethylene sulfide and pentamethylene disulfide in 7.1 % and 12.8% yields, respectively.

(g) Reaction of 1,5-Dibromopentane with Thioaceatmide with Alumina under Argon.

The reaction was carried out according to the procedure used in the reaction of 1,5-dibromopentane with thioacetamide on alumina in air (page 99). However, this reaction was carried out under argon. Only traces of pentamethylene sulfide and pentamethylene disulfide were found by GC/MS analysis.

(h) Reaction of 1,5-Dibromopentane with Thioacetamide and Silica Gel

To a mixture of 1,5-dibromopentane (0.23 g, 1.0 mmol) dissolved in 15 ml of toluene and 1.00 gram of silica gel (Davisil, grade 645, 60-100 mesh) in a 100 ml round bottom flask was added 1.23 g (2.0 mmol) of thioacetamide. The reaction mixture was slurried, worked up and analyzed according to the procedure described for the reaction of 1,5-dibromopentane with thioacetamide on unactivated alumina (page 99). The

product mixture contained two products identified as pentamethylene sulfide and pentamethylene disulfide in 25.3% and 26.4% yield, respectively.

vii. Reaction of Alkyl Monohalides with Thioacetamide and Alumina.

(a) Reaction of 1-Iodobutane with Thioacetamide and Alumina. General Procedure D.

To a solution of 1-iodobutane (0.170 g, 1.0 mmol) in 10 ml of toluene in a 100 ml round bottom flask was added 1.23 g (2.0 mmol) of thioacetamide and 1.00 gram of alumina. The reaction was slurried in refluxing toluene under argon for 10 hours and, after cooling, the product mixture was extracted with three 35 ml portions of anhydrous diethyl ether. After removing the solid by filtration through filter paper, the anhydrous diethyl ether and toluene were removed by evaporating under vacuum at 65°C using a rotovap. The product was isolated by preparative gas chromatography. The isolated product was identified as di-*n*-butyl disulfide in 56.5% yield: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 0.97 (t, 6 H, ($\underline{CH_3}$)), 1.58 (m, 8H, $CH_3(\underline{CH_2})_2CH_2S$), 2.70 (t, 4H, $(\underline{CH_2})_2S_2$). (lit.[20] (δ CCl_4): 0.95, 1.57, 2.70); MS, calc'd for $C_6H_{14}S_2$ m/z 118.2, found m/z 118.

(b) Reaction of 1-Bromobutane with Thioaceatmide and Alumina

As with the synthesis of *n*-butyl disulfide above, the reaction of 0.137 g (1.0 mmol) of 1-bromobutane, 1.00 gram of alumina and 1.23 g (2.0 mmol) of thioacetamide gave 45.8% of di-*n*-butyl disulfide: ^{1}H NMR (90 MHz, $CDCl_3$) δ: 0.97 (t, 6 H, ($\underline{CH_3}$)), 1.58 (m, 8H, $CH_3(\underline{CH_2})_2CH_2S$), 2.70 (t, 4H, $(\underline{CH_2})_2S_2$). (lit.[20] (CCl_4) δ: 0.95, 1.57, 2.70); MS, calc'd for $C_6H_{14}S_2$ m/z 118.2, found m/z 118.

REFERENCES

1. Ruzicka, L.; Stoll, M.; Schinz, H. *Helv. Chim. Acta* **1926**, *9*, 249.
2. Ziegler, K.; Eberle, H.; Ohlinger, H. *Liebig's Ann. Chem.* **1933**, *504*, 94.
3. (a) Galli, C.; Mandolini, L.; *Gazz. Chim. Ital.* **1975**, *105*, 367. (b) Illuminati, G.; Mandolini, L. *Acc. Chem. Res.* **1981**, *14*, 95.
4. Ruggli, P. *Leibig's Ann. Chem.* **1912**, *392*, 92; ibid, **1913**, *399*, 174; ibid, **1916**, *412*, 1.
5. Czech, B.; Quici, S.; Regen, S. L. *Synth. Commun.* 1980, 10, 113.
6. Ziegler, K.; Aurnhammer, R. *Liebig's Ann. Chim.* **1934**, *514*, 43.
7. (a) Friedman, P.; Allen, P. *J. Org. Chem.* **1965**, *30*, 780; (b) Degering, E. F.; Boatright, L. G. *J. Am. Chem. Soc.* **1950**, *72*, 5137.
8. Mandolini, L.; Vontor, T. *Synth. Commun.* **1979**, *9*, 857.
9. Peri, J. B. *J. Phys. Chem.* **1965**, *69*, 220.
10. Knözinger, H.; Ratmasany, P. *Catal. Rev- Sci. Eng.* **1978**, *17*, 31.
11. Harpp, D. N.; Gingras, M. *Tetrahedron Lett.* **1987**, *28*, 4374.
12. Slowinski, E. J.; Wolsey, W. C.; Masterton, W. L. *Chemical Principles in the Laboratory; 5th ed.*; Saunders College Publishing, Philadelphia, PA: **1989**, pp. 325-328.
13. Nicolaou, K. C. *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 1272.
14. Harpp, D. N.; Gingras, M. *J. Am. Chem. Soc.*, **1988**, *110*, 7737.
15. Harpp, D. N.; Gingras, M.; Aida, T.; Chan, T. H. *Synthesis*. **1987**, 1122.

16. (a) Vögtle, F.; Schunder, L. *Chem. Ber.* **1969**, *102*, 2682. (b) Sato, T.; Wakabayashi, M. *Tetrahedron Lett.* **1968**, 4188.

17. Vögtle, F.; Schunder, L. *Chem. Ber.* **1969**, *102*, 2677.

18. Vogel, P. *Carbocation Chemistry*; Elsevier Science Publishers, New York: **1985**, pp. 26.

19. Pouchert, C. J.; Campbell, J. R. *The Aldrich Library of NMR Spectra*; Aldrich Chemical Company, Milwaukee: **1974.**

20. *The Sadtler Standard Spectra (^1H NMR)*, Sadtler Research Laboratories, Philadelphia: **1987**.

21. Gaetano, K.; Pagni, R. M.; Kabalka, G. W.; Bridwell, P.; Walsh, E.; True, J. Underwood, M. *J. Org. Chem.* **1985**, 50, 499.

PART II

CHEMICAL AND PHYSICAL CHARACTERIZATION OF OF Al_2O_3 AND MODIFIED Al_2O_3

CHAPTER 1

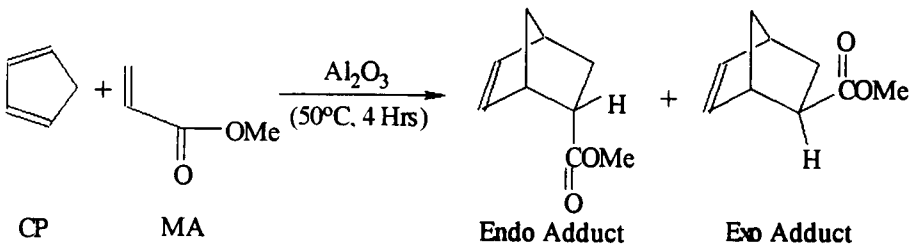
INTRODUCTION

More and more, chemists are studying organic reactions promoted by chromatographic gamma-alumina (γ-Al_2O_3).[1] γ-Alumina has long been used as an industrial catalyst, in column chromatography, and as an adsorbant. Cracking of petroleum[1] is an example of a useful industrial operation using alumina as a catalyst.

Although catalytic aluminas are less popular in industrial processes than other catalysts, they are, nonetheless, widely used as catalysts for several groups of reactions.[1,28,29] These reactions, which include many small scale laboratory reactions, are often run under mild conditions (< 100°C). In addition, many alumina-promoted organic reactions often are chemospecific, regiospecific, or stereospecific. Product isolation in these heterogeneous reactions is generally easier than the corresponding homogeneous reactions. Many interesting examples of alumina-promoted organic reactions have been summarized by Laslzo.[4] Among the many interesting alumina-promoted organic reactions are the acylation of aryl amines and alcohols by ethyl acetate.[5] In an example of a transesterification reaction, ethyl acetate was used as solvent and as acylating reagent; it reacted with primary alcohols to produce esters on the gram scale in 64% to 99% yield (eq 1).[5]

$$RCH_2\text{-}OH + EtO\overset{O}{\overset{\|}{C}}CH_3 \xrightarrow[25\text{-}30^{o}C,\ 1\ Hr]{Al_2O_3} RCH_2\text{-}O\overset{O}{\overset{\|}{C}}CH_3 \quad (64\text{-}99\%) \qquad (1)$$

In a study of the alumina-promoted Diels-Alder reaction, Parlar and Baumann demonstrated that the cycloaddition reaction of 1,3-cyclopentadiene and methyl acrylate gave almost exclusively (>30:1) the endo adduct (eq 2). When the reaction is run in solution, the ratio of endo to exo adducts is close to 3:1 ratio.[2]



(2)

Hondrogiannis *et al.*,[6] on the other hand, discovered that the cycloaddition of 1,3-cyclopentadiene and methyl acrylate is more complicated than that reported by Parlar and Baumann.[2] When the cycloaddition was run for 5 hours at 50°C on alumina which had been activated at various temperatures,[7] the endo to exo ratio of the adducts showed temperature dependence. The endo to exo ratio is 3 on unactivated, out-of-the-bottle alumina, and rises slowly to values between 7 - 10, depending on the loading of reactants,[8] on alumina activated at 300°C. The ratio then sharply rises to 40 - 50 on alumina activated at 400°C, again depending on the loading of the reactants.[8]

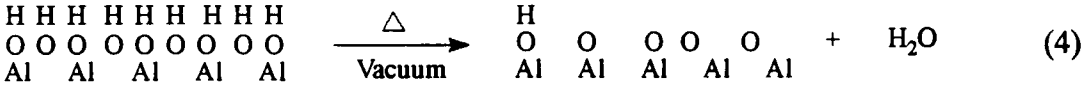
Pagni, Kabalka and coworkers[9] have also reported that alumina catalyzes the facile iodination of aromatic compounds using I_2 (eq 3). This reaction is difficult to perform in solution.



(3)

In Solution	8.4%
Al_2O_3 dehydrated at 400°C for 20 hours under vacuum	26.0%

These few examples show that γ-alumina catalyses a variety of chemical reactions. There is, unfortunately, only a limited understanding of how these reactions occur because the nature of the surface of alumina is poorly understood. Several theories of the surface of alumina do exist. Peri[10] and Knözinger and Ratnasamy[1] proposed that alumina has a layer of surface hydroxyls immediately above a layer of aluminum cations. When the solid is heated under vacuum, adjacent hydroxyl groups react to form water which is driven from the surface (eq 4).



(4)

The removal of adjacent hydroxyl groups in the form of water from alumina surfaces is essential for the development of catalytic activity. As a consequence of the removal of hydroxyl groups (surface ligands), coordinatively unsaturated anions (oxygen anions) and cations sites (exposed Al^{+3}) are created (Figure II-1).[1] These sites are involved in chemisorption and catalysis.

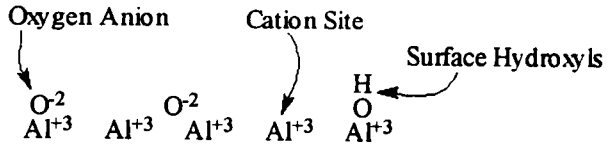


Figure II-1. Dehydrated Alumina.

We have used the surface of alumina to carry out a variety of organic reactions, including the cyclization of alkyl dihalides with sodium sulfide to form cyclic sulfides,

the reaction of tri-*n*-butyltinsulfide with the F^-/Al_2O_3 complex to form sulfide *in situ*, and the reactions of alkyl dihalides with thioacetamide on alumina to yield cyclic sulfides and disulfides, which were discussed in Part I. We have also recently prepared the BBr_3/Al_2O_3 complexes, which were used to catalyze Diels-Alder reactions; this chemistry is discussed in Part III of this dissertation.

In order to understand how organic reactions occur on alumina, it would be helpful to have a better knowledge of the surface characteristics of these aluminas and modified aluminas. A number of experiments were performed to characterize these solids. These included:

(A) Treatment of Al_2O_3 with CCl_4 to determine of the number of anions (O^{-2}) on the surface of alumina. The number of O^{-2} anions on the surface is assumed to be proportional to the number of CCl_4s which react by the reaction: $CCl_4 + O^{-2} \rightarrow {}^-OCCl_3 + Cl^-$. The pH of distilled water slurried with the CCl_4 treated aluminas was also measured.

(B) Qualitative and quantitative measurement of the acid strengths of the Al_2O_3 and modified alumina using Hammett indicators and by the amine titration method; and

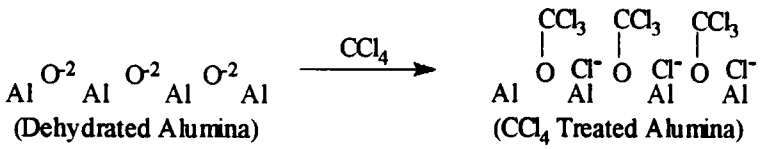
(C) Solid state ^{27}Al, ^{11}B and ^{31}P NMR analysis on alumina and modified aluminas.

CHAPTER 2

RESULTS AND DISCUSSION

A. Treatment of Al_2O_3 with CCl_4.

As discussed earlier, when alumina is heated under vacuum, adjacent hydroxyl groups react to form water, which is driven from the surface (eq 4, page 155). As a result of this reaction, surface oxide anions (O^{-2}s) are created and aluminum cations are partially exposed to the surface. The number of anions and cations created depends on the temperature at which the alumina is heated.[1,10] It was discovered in earlier work that CCl_4 reacts with the surface by what is presumed to be the S_N2 reaction of O^{-2} with CCl_4 (eq 5).[22] This reaction was examined as a possible method to quantitate the number of oxide anions (O^{-2}s) that are on the surface of alumina. If true, the number of O^{-2} anions on the surface will be proportional to the number of CCl_4s which are chemisorbed to the surface (eq 5). Justification for this hypothesis will be given later.



(5)

Because the method of treating the alumina with CCl_4 is the same for all the aluminas activated at various temperatures, the differences in the amount of CCl_4 chemisorbed on these aluminas can be compared. The number of moles of chemisorbed CCl_4 per gram of Al_2O_3, CCl_4/Al_2O_3, can be calculated by the weight increase of the

solid, provided that no gaseous products are formed in the chemisorption reactions. The alumina (~ 20 grams) was first dehydrated at a given temperature under vacuum (< 5 x 10^{-3} torr) for 20 hours. The weight loss of alumina (due to the loss of H_2O) was measured. The results are recorded in Table II-1 and shown graphically in Figure II-2. It can be seen that the weight losses of aluminas increase as the activation temperature increases. The dehydrated alumina was then slurried with an excess amount of CCl_4 (50.0 ml) for 20 hours at room temperature after which any unreacted solvent was removed under vacuum at 55°C. The difference in weight between the dehydrated alumina and the weight of alumina treated with CCl_4 at room temperature was then measured. These results are recorded in Table II-2 and shown graphically in Figure II-3.

Table II-1. Dehydration of Alumina at Different Temperatures.[a,b]

Temperature of Dehydration (°C)	Initial Weight of Alumina (g)	Weight of Alumina After Dehydration (g)	Weight Loss of Alumina After Dehydration (g)
100	20.005	18.750	1.255
175	20.004	17.553	2.451
250	20.007	16.739	3.268
325	20.006	15.659	4.347
400	20.006	15.428	4.578

[a] Alumina was dehydrated for 20 hours.

[b] Alumina was dehydrated using the appartus designed by Pagni, Kabalka, *et al.*[11]

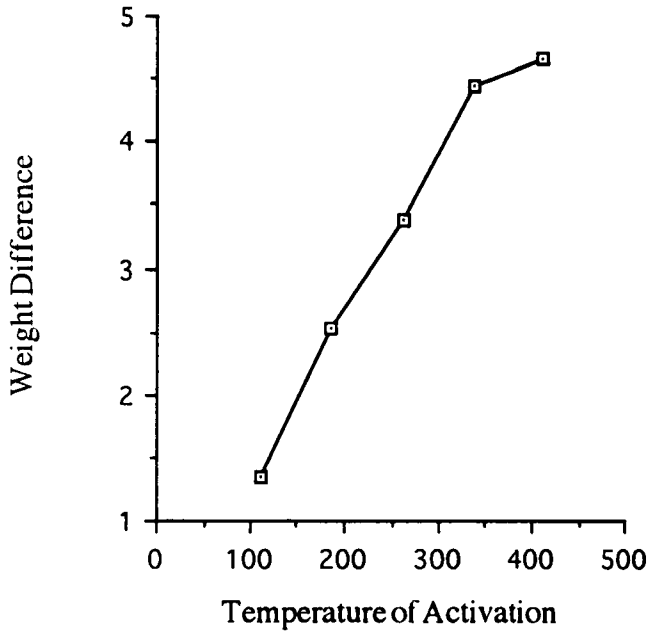


Figure II-2. The Weight Difference between the Dehydrated Alumina and the Initial Weight of the Alumina versus the Temperature at which the Alumina was Dehydrated.

Table II-2. Weight Difference between the Initial Dehydrated Alumina and Alumina Treated with CCl_4 (50 ml) at Room Temperature.

Temperature of Dehydration (°C)	Initial Weight of Dehydrated Alumina (g)	Weight of Alumina Treated with CCl_4 (g)	Weight Difference (g)
Unact'd(25°C)[a]	20.003	19.832	-0.171
100	18.750	19.042	0.292
175	17.553	18.381	0.828
250	16.739	18.128	1.389
325	15.659	19.783	4.124
400	15.438	20.209	4.781

[a]Unactivated = The alumina was used directly from a previously unopened bottle.

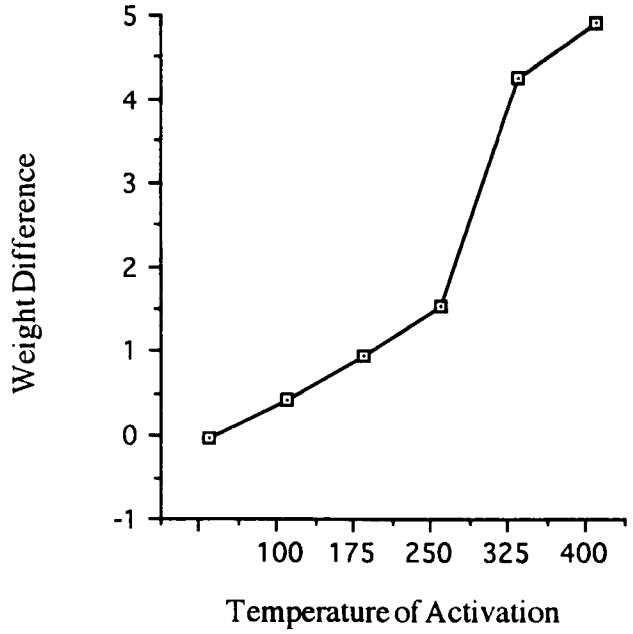
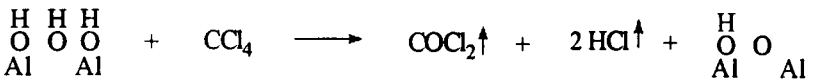


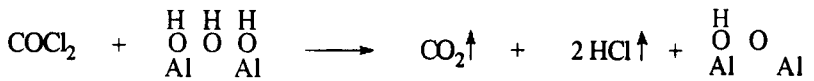
Figure II-3. Plot of the Weight Difference between the Initial Dehydrated Alumina and the Alumina Treated with CCl_4 at Room Temperature versus the Temperature at which the Alumina was Dehydrated.

Clearly, alumina dehydrated at higher temperatures showed significantly greater weight increases when treated with CCl_4 than alumina dehydrated at lower temperatures. This is reasonable because alumina dehydrated at higher temperature contains more surface O^{-2} groups than alumina dehydrated at lower temperatures. The increase in the number of O^{-2} anions is responsible for the increase in weight due to the reaction with CCl_4 (eq 5, page 111). However, when unactivated alumina was treated with CCl_4, a weight decrease in the CCl_4 treated alumina was observed. One can give a plausible, but unproven explanation. Unlike activated alumina, unactivated alumina does not have partially exposed O^{-2} anions which can react with CCl_4. Instead, unactivated alumina has a surface layer of hydroxyl groups which react with CCl_4 in a different manner, leading to the formation of $OCCl_2$ (phosgene) and HCl (eq 6). The phosgene then reacts further

to give CO_2 and HCl (eq 7).[12] The formation and loss of gaseous HCl and CO_2 account for the weight decrease of unactivated alumina.



(6)



(7)

The number of moles of chemisorbed CCl_4 per gram of Al_2O_3 and the number of moles of chemisorbed CCl_4 per cm^2 of Al_2O_3 were calculated and are shown in Tables II-3 and II-4, respectively. The data are also shown graphically in Figure II-4 and II-5. The calculations to determine these numbers are shown in the EXPERIMENTAL SECTION, page 160. The number of CCl_4/gram of Al_2O_3 was converted to the number of CCl_4/cm^2 Al_2O_3 by assuming that the surface area of alumina is 155 m^2/g Al_2O_3 in all cases.[1,10]

Table II-3. The Number of CCl_4 per gram of Al_2O_3 for CCl_4 Treated Alumina (Slurried at Room Temperature).

Amount of dehydrated Al_2O_3 used	Temp. & Duration of Dehydration	Amount of CCl_4 used	Number of CCl_4/gram Al_2O_3
18.750g	100°C/20 hrs.	50.0 ml	6.09×10^{19}
17.553 g	175°C/20 hrs.	50.0 ml	1.85×10^{20}
16.739 g	250°C/20 hrs	50.0 ml	3.24×10^{20}
15.659 g	325°C/20 hrs	50.0 ml	1.03×10^{21}
15.438 g	400°C/20 hrs	50.0 ml	1.21×10^{21}

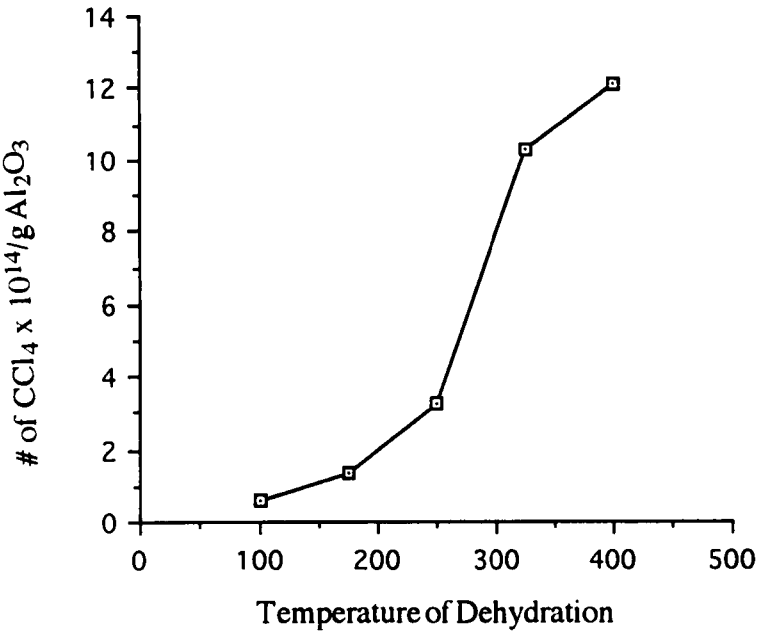


Figure II-4. Plot of the Number of CCl_4/gram of Alumina versus the Temperature at which the Alumina was Dehydrated.

Table II-4. The Number of CCl_4 per cm^2 of Al_2O_3 for the CCl_4 Treated Alumina (Slurried at Room Temperature).

Amount of dehydrated Al_2O_3 used	Temp. & Duration of Dehydration	Amount of CCl_4 used	Number of CCl_4/cm^2 Al_2O_3
18.750g	100°C/20 hrs.	50.0 ml	$3.93x10^{13}$
17.553 g	175°C/20 hrs.	50.0 ml	$8.97x10^{13}$
16.739 g	250°C/20 hrs	50.0 ml	$2.09x10^{14}$
15.659 g	325°C/20 hrs	50.0 ml	$6.64x10^{14}$
15.438 g	400°C/20 hrs	50.0 ml	$7.82x10^{14}$

Figure II-5 contains two plots: (1) the experimental number of CCl_4/cm^2 Al_2O_3 vs. activation temperature and (2) the theoretical values of the oxide concentration (the number of O^{-2}/cm^2 vs activation temperature) taken from the work of Knözinger and Ratnasamy.[1]

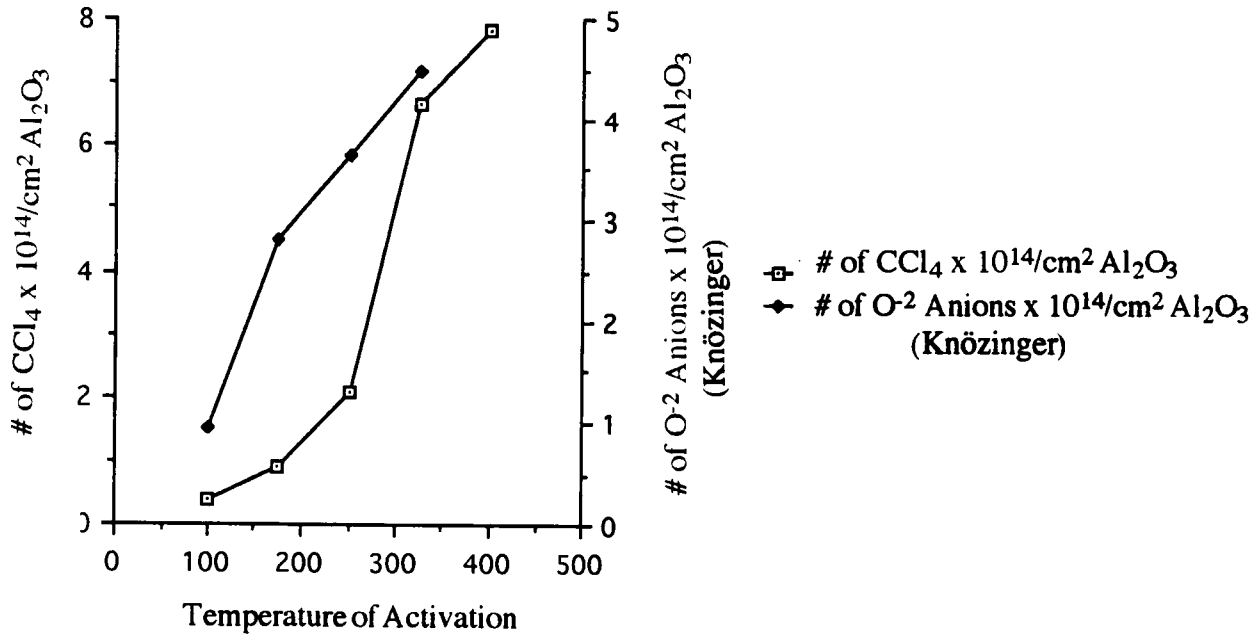


Figure II-5. Comparison of the Number of CCl_4/cm^2 of Alumina Obtained by the Treatment of Alumina with CCl_4 and the Number of $O^{-2}s/cm^2$ Calculated by Knözinger and Ratnasamy.

The two curves are remarkably similar, which suggest that indeed one CCl_4 is chemisorbed for every O^{-2} on the surface. The difference in the two curves probably arises because of uncertainty in the theorectically derived values and the assumption made in this work that the surface area of alumina remains constant. It is well known that the surface area of alumina changes when is treated with CCl_4 at high temperatures. When dehydrated alumina was treated with CCl_4 at 70°C instead of room temperature, the results were, surprisingly, quite different. The data from these experiments are shown in Table II-5 and Figure II-6.

Table II-5. Weight Difference Between the Initial Dehydrated Alumina and Alumina Treated with CCl_4 (50.0 ml) at 70°C.

Temperature of Dehydration (°C)	Initial Weight of Dehydrated Alumina (g)	Weight of Alumina treated with CCl_4 at 70°C	Weight Difference (g)
unact'd(25°C)[a]	20.002	20.823	0.821
100	20.003	24.985	4.982
175	20.003	24.821	4.818
200	20.005	23.018	3.013
325	20.004	19.790	-0.214
400	20.003	20.191	0.188

[a] Unactivated = The alumina was taken directly from a new bottle of solid.

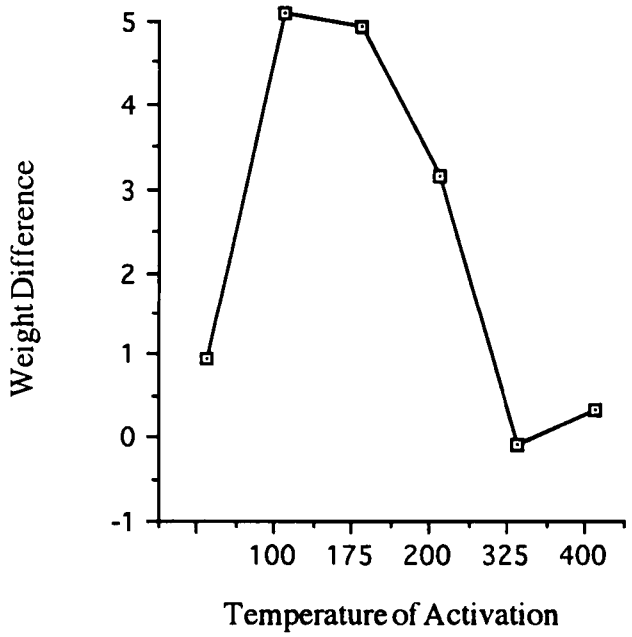
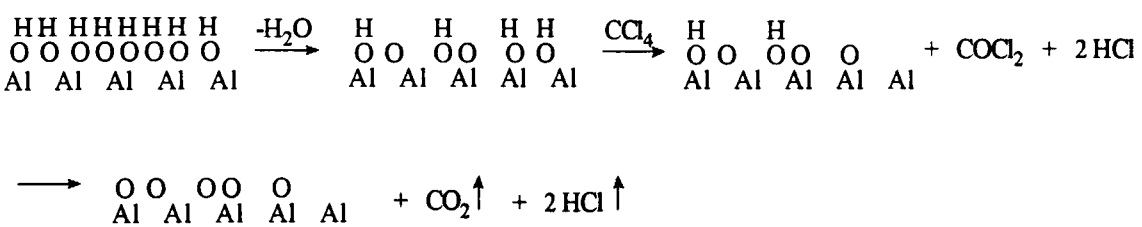


Figure II-6. The Weight Difference between the Initial Dehydrated Alumina and the Alumina Treated with CCl_4 at 70°C and the Temperature at which the Alumina is Activated.

The data in Table II-5 and Figure II-6 show a trend quite different than that shown in Table II-2 and Figure II-3: the weight change goes up at first, then goes down, and finally goes up again. This behavior can be qualitatively rationalized as follows. There was a large weight gain on going from CCl_4/Al_2O_3(unactivated) to the CCl_4/Al_2O_3(100°C). However, the weight gain started to decrease gradually for the CCl_4/Al_2O_3(175°C) and CCl_4/Al_2O_3(200°C), respectively. Some combination of weight increase and decrease must be used to explain this behavior. The weight increase will arise by chemistry already described. The weight decrease, on the other hand, must be due to the reactions not observed when the reactions are performed at room temperature. When the dehydrated alumina was treated with CCl_4 at 70°C, the oxide anions react with CCl_4 to form phosgene which is then driven off the surface of the alumina. The phosgene then reacts further with remaining hydroxyl groups to give CO_2 and HCl. The formation and loss of gaseous CO_2 and HCl account for the weight gain for the CCl_4/Al_2O_3 (Scheme II-1). No attempt was made, however, to collect and identify these gaseous compounds.

Scheme II-1. Reaction that may Account for the Increased Weight Loss in the CCl_4/Al_2O_3 Slurried at 70°C.



In addition to measuring weight changes for the CCl_4 treated aluminas, the pHs of these solids were also determined with a pH meter. This was performed to see what happens when the CCl_4 treated aluminas are rehydrated with distilled water. All the measurements were taken while the samples were being stirred in distilled water. 6.00 grams of the CCl_4 treated alumina and 10.0 ml of distilled water were used in each experiment, and each sample was stirred at the same rate at room temperature. Table II-6 shows the results of the pH measurements for alumina that was treated with CCl_4 at room temperature, and Figure II-7 displays the data graphically.

Table II-6. pH Measurements of Distilled Water Slurried with Alumina Previously Treated with CCl_4 at Room Temperature.[a]

Solution	pH	Wt. Increase[b]
Distilled H_2O	6.69	-
CCl_4/Al_2O_3 (unact'd)[c] in distilled H_2O	7.42	-0.171
CCl_4/Al_2O_3 (100°)[d] in distilled H_2O	5.35	0.292
CCl_4/Al_2O_3 (175°)[d] in distilled H_2O	4.74	0.828
CCl_4/Al_2O_3 (250°)[d] in distilled H_2O	4.43	1.389
CCl_4/Al_2O_3 (325°)[d] in distilled H_2O	4.35	4.124
CCl_4/Al_2O_3 (400°)[d] in distilled H_2O	4.28	4.781

[a] 6.00 g of CCl_4/Al_2O_3 + 10.0 mL of distilled H_2O. [b]Wt. Increase = Weight of Al_2O_3 treated with CCl_4 at room temperature minus Initial Weight of dehydrated Al_2O_3

[c]Unact'd = Alumina was used fresh from the bottle. [d]Al_2O_3 (°C) = Alumina was dehydrated for 20 hours at the indicated temperature before treatment with CCl_4.

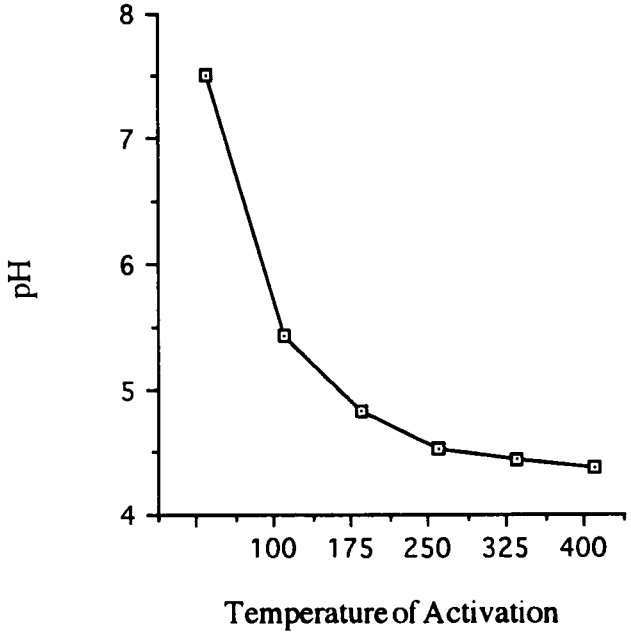
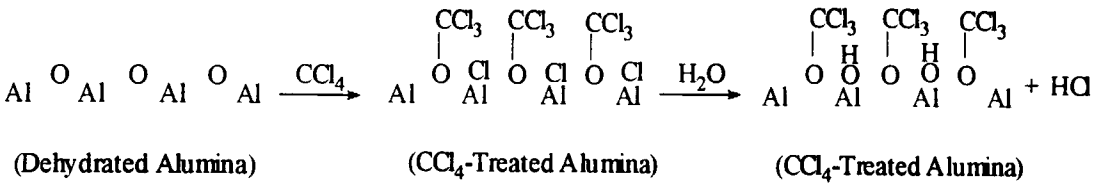


Figure II-7. pH of Distilled H_2O Slurried with Al_2O_3 Treated with CCl_4 at Room Temperature Versus the Temperature at which the Al_2O_3 (6.00 g) was Dehydrated before Treatment with CCl_4.

Clearly, an increase in the temperature of dehydration of the alumina decreases the pH values of the water. Alumina dehydrated at higher temperatures loses more water by the reaction between adjacent hydroxyl groups than alumina dehydrated at lower temperatures. Therefore, more exposed O^{-2} anions and Al^{+3} cations are available for the chemsorption of CCl_4 for alumina dehydrated at higher temperatures. When this CCl_4-treated alumina is stirred with distilled H_2O, HCl is evolved by hydrolysis of Al-Cl bonds, thus resulting in a more acidic aqueous solution (Scheme II-2). One can conclude that there is a correlation between the weight increase of the alumina treated with CCl_4 and the amount of HCl evolved.

Scheme II-2. Evolution of HCl when CCl_4/Al_2O_3 is Stirred with Distilled H_2O.



The pHs of aluminas treated with CCl_4 at 70°C were also determined with a pH meter. The measurements were done according to the procedure just described above. These results are summarized in Table II-7 and Figure II-8.

Table II-7. pH Measurments of Distilled H_2O Slurried with Alumina[a] Treated with CCl_4 at 70°C.

Solution	pH
Distilled H_2O	6.69
Al_2O_3 (Unactivated)[b] in distilled H_2O[d]	6.62
CCl_4/Al_2O_3 (Unact'd)[b] in distilled H_2O[d]	9.68
CCl_4/Al_2O_3 (100°)[c] in distilled H_2O[d]	9.22
CCl_4/Al_2O_3 (175°)[c] in distilled H_2O[d]	9.34
CCl_4/Al_2O_3 (250°)[c] in distilled H_2O[d]	9.96
CCl_4/Al_2O_3 (325°)[c] in distilled H_2O[d]	11.08
CCl_4/Al_2O_3 (400°)[c] in distilled H_2O[d]	11.82

[a]6.00 g of Alumina was used. [b]Unactivated = Alumina was used fresh from the bottle. [c]Al_2O_3 (°C) = Alumina was dehydrated for 20 hours at the indicated temperature before treatment with CCl_4. [d] 10.0 ml of distilled H_2O was used.

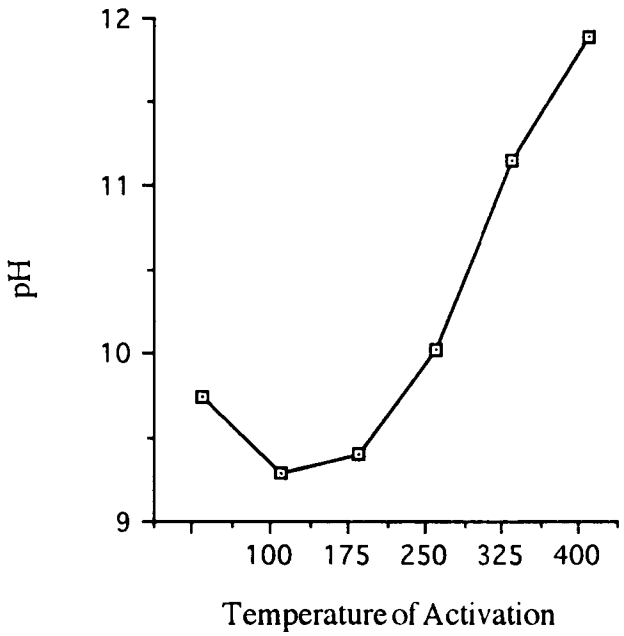


Figure II-8. Plot of pH of Distilled H_2O (10.0 mL) Slurried with Alumina Treated with CCl_4 at 70°C versus the Temperature at which the Alumina was Dehydrated before Treatment with CCl_4.

When the CCl_4 and the dehydrated alumina were slurried at 70°C, the pH values were much higher than the pH values recorded for the alumina treated with CCl_4 at room temperature. A different trend in pH is also apparent. An increase in the temperature of alumina activated resulted in an increase in the pH values of the distilled water. However, the reason for the increase in pH value is not clear.

B. Measurement of the Acidity and the Basicity of Alumina and Modified Alumina Surfaces.

Background

The importance of solid acid catalysts in the refining of petroleum by cracking, hydrocracking and isomerization chemistry has stimulated a considerable amount of research on the measurement of the acidity of solid surfaces.[1] Among the large variety of solid acids used in this type of chemistry are natural occurring clays, alumina, silica-alumina, magnesium sulfate and zeolites.[4]

The reactivity and selectivity of surface reactions occurring by acid catalysis are, to a large extent, dependent on the surface acidity of the catalyst.[15] According to Mirodatos *et al.*,[16] "Lewis acid sites in the vicinity of protonic sites can increase the reactivity of these protonic sites."

Because the acidity of solids usually plays a pivotal role in surface-catalysed reactions, joint participation by adjacent acid sites on the solid may influence catalytic properties even more. For example, when alumina is treated with BBr_3, BF_3 and BCl_3, the resulting solid has boron and aluminum sites which may act coorperatively to catalyze, for example, the Diels-Alder reaction. Reactions of this type will be discussed further in Part III.

It is important to find convenient and accurate methods for characterizing the acidity of aluminas and modified aluminas used in our work. The method chosen for this characterization is based on the chemisorption of base indicators which was popularized

by Benesi.[23] Benesi measured the acid strength of solid surfaces by noting the colors of adsorbed Hammett base indicators.[17] The color of the adsorbed indicators gives a measure of its acid strength. In addition to measuring the acid strength of solid surfaces, Hammett acid indicators can be used in the same way to measure the base strength of solid surfaces. The Hammett base and acid indicators used in this study are shown in Tables II-8 and II-9, respectively.

Table II-8 contains a list of six Hammett base indicators of varying strengths, together with the color changes which occur at the indicated H_os. The sulfuric acid compositions, corresponding to the mid-point of each of the acid-base color transitions, are included to give an idea of the vast acid strength range covered by these indicators. The limits of the acidity function (H_o) of a surface are established by observing the color of the adsorbed form of the Hammett indicators. For example, a solid having an H_o between -3.0 to -8.2 give a red color with dicinnamalacetone and no color with anthraquinone. A solid with an $H_o < -8.2$, however, would give a color with anthraquinone.

In addition to measuring the H_o of the aluminas and modified aluminas, the number of acid sites at a given H_o was also measured by titrating with *n*-butylamine for many of these solids. pHs of distilled water suspension of the solids were also determined.

The solids studied were alumina, dehydrated alumina, the solids modified by treatment with boron halide and CCl_4. Detailed discussion on the methods used to prepare these solids and modified solids are given in the EXPERIMENTAL SECTION.

Table II-8. Base Indicators Used for the Measurement of Acid Strength.[17]

Indicator	Color			H_2SO_4[b]
	Base form	Acid form	pK_a[a]	%
Methyl red	yellow	red	+4.8	-
p-Dimethylaminoazobenzene (Dimethyl Yellow)	yellow	red	+3.3	3×10^{-4}
2-Amino-5-azotoluene (Fast Garnet)	yellow	red	+2.0	5×10^{-3}
Crystal violet	blue	yellow	+0.8	0.1
Dicinnamalacetone	yellow	red	-3.0	48
Anthraquinone	colorless	yellow	-8.2	90
m-Nitrochlorobenzene	colorless	yellow	-13.2	>90

[a]The pK_a of the indicator coresponds to H_o (acidity function) of the medium.
[b]wt % of H_2SO_4 in sulfuric acid solution has the acid strength corresponding to the respective pK_a.

Table II-9. Indicators Used for the Measurement of Basic Properties.[17]

Acid Indicators	Color		pK_a
	Acid form	Base form	
Bromothymol blue	yellow	green	7.2
2,4-Dinitroaniline	yellow	violet	15.0
4-Nitroaniline	yellow	orange	18.4
4-Chloroaniline	colorless	pink	26.5

Results and Discussion.

Determination of the pK_a of Solid Surfaces Using Base Indicators.

Base indicators (Table II-8) were adsorbed on a given solid surface in cyclohexane solutions. If the adsorbed indicator gave the color of its acid form, the value of H_o for the surface is equal to or lower than the pK_a of the indicator. The lower the determined

H_o value is, the greater is the acid strength of the surface. For example, the solid which gives a yellow coloration with anthraquinone (pK_a = -8.2) has an acid strength which is smaller than H_o = -8.2. A solid which gives a red coloration with a dicinnamalacetone (pK_a = -3.0) but no color with anthraquinone has an acid strength which lies between H_o = -3.0 and -8.2.

The results on a number of the solids and modified solids are presented in Table II-10 and II-11.

Table 10. Colors of Base Indicators Adsorbed on Unactivated and Activated Aluminas.

Indicators	Methyl Red	Methyl Yellow	Fast Garnet	Crystal Violet	Dicinnamal-acetone	Anthra-quinone	*m*-Nitro-chloro-benzene
Color Change[a] Base form → Acid form	Y → R	Y → R	Y → R	B → Y	Y → R	Cl → Y	Cl → Y
pK_a	+6.8	+4.8	+2.0	+0.8	-3.0	-8.2	-13.2
Unact'd and Act'd Aluminas							
Al_2O_3 (Unact'd)[b]	Y	Y	Y	B	Y	Cl	Cl
Al_2O_3 (100°C)[c]	Y-R	Y-R	Y	B	Y-R	Cl	Cl
Al_2O_3 (200°C)[c]	R	R	R	Y	R	Cl	Cl
Al_2O_3 (300°C)[c]	R	R	R	Y	R	Cl	Cl
Al_2O_3 (400°C)[c]	R	R	R	Y	R	Cl	Cl

[a]R = red, Y = yellow, B = blue, Cl = colorless, Y-R = partial adsorption as conjugate acid, and an intermediate color.
[b]Unact'd = Alumina was used fresh from the bottle.
[c]Activation temperature in parenthesis.

Table 11. Colors of Basic Indicators Adsorbed on Modified Solids.

Indicators	Methyl Red	Methyl Yellow	Fast Garnet	Crystal Violet	Dicinnamal-acetone	Anthra-quinone	*m*-Nitro-chloro-benzene
Color Change[a] Baseform→ Acid form	Y → R	Y → R	Y → R	B → Y	Y → R	Cl → Y	Cl → Y
pK_a	+6.8	+4.8	+2.0	+0.8	-3.0	-8.2	-13.2
Solids and Modified Solids							
BBr_3/Al_2O_3 (Unact'd)[d]	R	R	R	Y	R	Y	Y
BBr_3/Al_2O_3 (100°C)[b,c]	R	R	R	R	Y-R	Y	Y
BBr_3/Al_2O_3 (200°C)[b,c]	R	R	R	Y	Y-R	Y	Y
BBr_3/Al_2O_3 (300°C)[b,c]	R	R	R	Y	Y-R	Y	Y
BBr_3/Al_2O_3 (400°C)[b,c]	R	R	R	Y	R	Y	Y
BCl_3/Al_2O_3 (200°C)[b,c]	R	R	R	Y	Y-R	Cl	Cl
BF_3/Al_2O_3 (400°C)[b,c]	R	R	R	Y	Y	Cl	Cl

R = red, Y = yellow, B = blue, Cl = colorless, Y-R = partial adsorption as conjugate acid, and an intermediate color.

[b]Activation Temperature in Parenthesis.

[c]Alumina was first activated at the temperature in parenthesis, then treated with of boron trihalide.

[d] Unact'd = Alumina was used fresh from the bottle.

To provide a frame of reference for the surface acidities of the dehydrated aluminas and modified aluminas, the Hammett indicators were first applied to unactivated alumina taken directly out of the bottle. As was expected, this alumina did not have any strongly acidic properties because it gave no acid colors with any of the Hammett base indicators.

These results and those for the activated aluminas listed in Table II-10 and II-11 show, first of all, that the acidities of the aluminas are in the order: $Al_2O_3/400°C$ = $Al_2O_3/300°C$ = $Al_2O_3/200°C$ > $Al_2O_3/100°C$ > Al_2O_3/unactivated. Second, the BBr_3 treated aluminas are all very acidic and have comparable values. It should be noted, however, that the color of the adsorbed crystal violet on BBr_3/Al_2O_3 (unactivated) did not change from blue to yellow even though there was a color change from yellow to red in the adsorbed dicinnamalacetone. This may be due to the fact that the color changes are often difficult to detect because the colors are often weak and difficult to see. In addition, the color was observed after the solid and indicator/cyclohexane solution had been slurried for 5 minutes. The reactions occasionally are considerably slower and one might have to make the observations after a much longer time. Third, the acid strengths for the different boron trihalide treated aluminas are in the order: BBr_3/Al_2O_3 (400°C) > BCl_3/Al_2O_3 (200°C) > BF_3/Al_2O_3 (400°C). Interestingly, the acidity order of the boron trihalide treated aluminas is identical to the order of acidities of the pure boron trihalides where BBr_3 > BCl_3 > BF_3.[13] The acid strength of the boron trihalide, both in the pure state and on the alumina, is explained by the resonance effects of the halogen substituents. BF_3 is the weakest acid due to the greater resonance stabilization of BF_3 as compared to BCl_3, and BCl_3 has a greater resonance stabilization than BBr_3 (Figure II-9).[13] This can be attributed to the fact that fluorine is in the same period as boron and their 2 p orbitals are similar in size. The order of acidity of the boron trihalide treated aluminas can also be explained in the same manner (Figures II-10 and II-11).

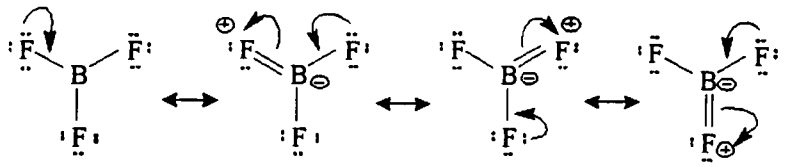


Figure II-9. Resonance Stabilization of BF_3.

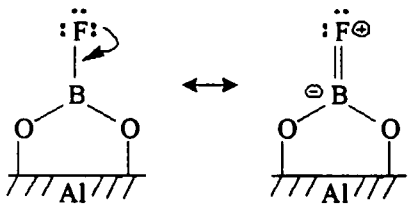


Figure II-10. Resonace Stabilization of BX_3/Al_2O_3.

The aluminas and boron tribromide treated aluminas (6.00 g) were also treated with 10 ml of H_2O and the pHs of the resulting solutions measured. The results are presented in Table II-12 and Figure II-11. One would expect the BBr_3/Al_2O_3s to have low pHs if there are any BBr bonds because hydrolysis will yield HBr. The results shown first of all, that, as the temperature at which the aluminas were activated increases, the acidity resulting from the alumina increases slightly. Analysis by the manufacturer (Aldrich Chemical Company) shows that there are 3 x 10^{-3} moles of Cl^- /gram Al_2O_3 in the unactivated alumina. Some of this Cl^- becomes exposed when the alumina is activated; a higher temperature of activation will result in a greater number of exposed Cl^-. If the surface Cl^- is complexed to Al^{+3} ions, hydrolysis of the Al-Cl bonds will produce aqueous HCl. As expected, hydrolysis of the BBr_3/Al_2O_3 does yield a significantly lower pH values, but it is difficult to explain the trend in pH values. However, the results in Table II-12 clearly shows that the acidities of the BBr_3/Al_2O_3s are considerably higher than for the unactivated and activated aluminas. BBr_3 is believed to be adsorbed on the activated alumina as shown in Figure II-19 (a), page 155, where trigonal boron is bonded to one bromine atom and two oxygen atoms. (Details on how the BBr_3 is adsorbed onto the alumina is described on page 217 of Part III). When the BBr_3/Al_2O_3 is hydrolyzed, the B-Br bonds produce HBr. In addition, there may also be some Al-Br bonds on the surface which yield HBr on hydrolysis (eq 8 and eq 9).

$$\text{B-Br} + H_2O \rightleftarrows \text{B-OH} + \text{HBr} \qquad (8)$$

$$\text{Al-Br} + H_2O \rightleftarrows \text{Al-OH} + \text{HBr} \qquad (9)$$

Table II-12. pH Values of Dehydrated Aluminas, BBr_3 Treated Aluminas and BCl_3 Treated Aluminas (6.00 g) Treated with H_2O (10 mL)[a,9]

Solution	pH
Al_2O_3 (Unactivated)[a] in distilled H_2O	6.13
Al_2O_3 (100°C)[b] in distilled H_2O	5.72
Al_2O_3 (200°C)[b] in distilled H_2O	5.90
Al_2O_3 (300°C)[b] in distilled H_2O	5.67
Al_2O_3 (400°)[b] in distilled H_2O	5.58
BBr_3/Al_2O_3 (Unactivated)[a] in distilled H_2O	1.98
BBr_3/Al_2O_3 (100°C)[c] in distilled H_2O	4.05
BBr_3/Al_2O_3 (200°C)[c] in distilled H_2O	2.91
BBr_3/Al_2O_3 (300°C)[c] in distilled H_2O	2.76
BBr_3/Al_2O_3 (400°C)[c] in distilled H_2O	4.13

[a]Unactivated = Alumina was used directly from the bottle.
[b]Al_2O_3 (°C) = Alumina was dehydrated for 4 hours at the indicated temperature.
[c]BBr_3/Al_2O_3 (°C) = Alumina was dehydrated for 4 hours at the indicated temperature before treatment with the boron trihalide.

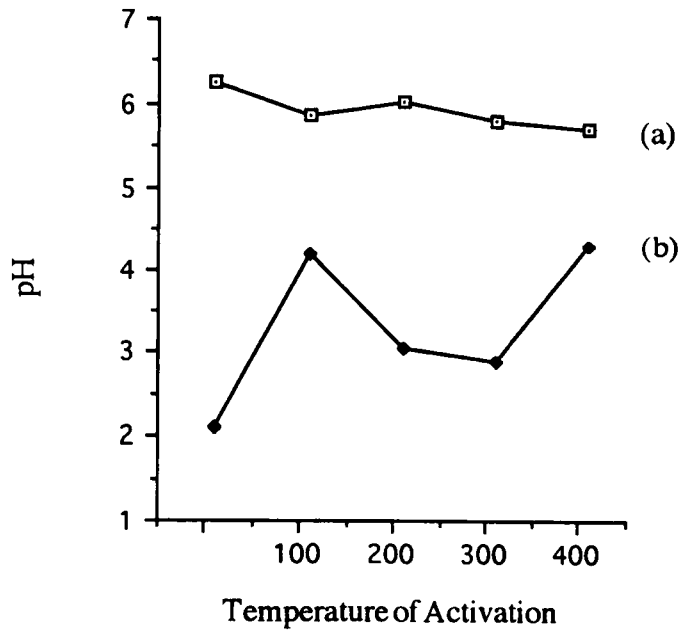


Figure II-11. pH Values versus Activation Temperature of (a) Al_2O_3; (b) BBr_3/Al_2O_3.

Additional acidity measurements were collected for CCl_4 treated alumina, and these are collected in Table II-13.

The data show that none of the CCl_4-treated aluminas, slurried at 70°C show any acidity. For the aluminas slurried with CCl_4 at room temperature, CCl_4/Al_2O_3 (400°C) has the highest acid strength based on the fact that the color of the adsorbed anthraquinone changed from clear to yellow while the color remained clear when anthraquinone is adsorbed on the other CCl_4/Al_2O_3s. CCl_4/Al_2O_3 (175°C) and CCl_4/Al_2O_3 (325°C), on the other hand, had $H_o \leq -3.0$, whereas CCl_4/Al_2O_3 (325°C) did not have any acid sites with an H_o of +2.0. Curiously, CCl_4/Al_2O_3 (100°C) had a greater acid strength than CCl_4/Al_2O_3 (unactivated), while CCl_4/Al_2O_3 (250°C) had the lowest acid strength of all the aluminas treated with CCl_4 at room temperature. The temperature at which the alumina was dehydrated before treatment of CCl_4 makes a profound difference in the acid strength of the resulting alumina. It is, however, difficult to explain the observed behavior. The CCl_4/Al_2O_3(100°C) stirred at room temperature, for example, displayed the acid form with methyl red, crystal violet and dicinnamalacetone. One would also have expected to observe a color change to the acid form with the methyl yellow and fast garnet, but this was not found. It should be noted again that the color changes are often quite difficult to detect because the colors are weak. Unfortunately, the measurements were not repeated. Another explanation is also possible. The color was typically observed after the solid and indicator/cyclohexane solution had been slurried for 5 minutes. It is known that in some cases the reactions are slow and one might have to make the observation after a considerably longer time.

Table II-13. Colors of Base Indicators Adsorbed on CCl_4 Modified Aluminas.

Indicators	Methyl Red	Methyl Yellow	Fast Garnet	Crystal Violet	Dicinnamal-acetone	Anthra-quinone
Color Change[a] Base form→ Acid form	Y → R	Y → R	Y → R	B → Y	Y → R	Cl-Y
pK_a	+4.8	+3.3	+2.0	+0.8	-3.0	-8.2
Modified Solids						
CCl_4/Al_2O_3 (Unactivated)[b] stirred at RT	light R	R	R	B	Y	Cl
CCl_4/Al_2O_3 (100°C)[b] stirred at RT	R	Y	Y	Y	R	Cl
CCl_4/Al_2O_3 (175°C)[b] stirred at RT	R	Y	R	Y	R	Cl
CCl_4/Al_2O_3 (250°C)[b] stirred at RT	Y	Y	Y	B	Y	Cl
CCl_4/Al_2O_3 (325°C)[b] stirred at RT	R	Y	Y	Y	R	Cl
CCl_4/Al_2O_3 (400°C)[b] stirred at RT	R	R	R	Y	R	Y
CCl_4/Al_2O_3 (Unactivated)[b] stirred at 70°C	Y	Y	Y	B	Y	Cl
CCl_4/Al_2O_3 (100°C)[b] stirred at 70°C	light R	Y	Y	Y	R	Y
CCl_4/Al_2O_3 (175°C)[b] stirred at 70°C	Y	Y	Y	B	Y	Cl
CCl_4/Al_2O_3 (250°C)[b] stirred at 70°C	Y	Y	Y	B	Y	Cl
CCl_4/Al_2O_3 (325°C)[b] stirred at 70°C	Y	Y	Y	B	Y	Cl
CCl_4/Al_2O_3 (400°C)[b] stirred at 70°C	Y	Y	Y	B	Y	Cl

[a]R = red, Y = yellow, B = blue, Cl = colorless,

[b]Activation Temperature in parenthesis.

Determination of the Basicity of Solid Surfaces Using Acidic Indicators:

In addition to using base indicators to measure the acid strengths of alumina and modified alumina, acid indicators were adsorbed onto the solids to measure their base strengths. The acid indicators used are listed in Table II-9 (p. 126). The procedure used to determine the basicity of the solids is identical to the procedure used to measure the acidity of the solids. However, the dyes were adsorbed onto the solids from benzene instead of cyclohexane. The results on the solids and modified solids are summarized in Table II-14. The data listed in Table II-14 show that unactivated alumina (Adsorption) has a higher base strength than unactivated Brockmann 1 alumina, but the difference is not large. All the activated aluminas showed a base strength of $pK_a < +7.2$.

The base strengths of the CCl_4 treated aluminas, slurried at room temperature, were also measured and are displayed in Table II-15. The observed base strengths are in the order: CCl_4/Al_2O_3 (unactivated) = CCl_4/Al_2O_3 (100°C) = CCl_4/Al_2O_3 (250°C) > CCl_4/Al_2O_3 (175°C) = CCl_4/Al_2O_3 (325°C) = CCl_4/Al_2O_3 (400°C). The base strengths of the CCl_4/Al_2O_3, slurried at 70°C, which are also reported in Table II-15, show a similar basic strength of $pK_a > +7.2$. It is presently not possible to rationalize these results. Further work will be required.

Table II-14. Colors of Acid Indicators Adsorbed on Aluminas.

Indicators	Bromothymol blue	2,4-Dinitro aniline	4-Nitro-aniline	4-Chloro-aniline
Color change[a] Acid form→ Base form	Y → G	Y → V	Y → O	Cl → P
pK_a	+7.2	+15.0	+18.4	+26.5
Solids and Modified Solids				
Al_2O_3(Brockman 1)[b] (Unactivated)[d]	Y	Y	Y	Cl
Al_2O_3(Adsorption)[c] (Unactivated)[d]	G	Y	Y	Cl
Al_2O_3 activated (100°C)[e]	Y	Y	Y	Cl
Al_2O_3 activated (200°C)[e]	Y	Y	Y	Cl
Al_2O_3 activated (300°C)[e]	Y	Y	Y	Cl
Al_2O_3 activated (400°C)[e]	Y	Y	Y	Cl

[a] G = green, Y = yellow, O = orange, V= violet, P = pink. [b] Al_2O_3 (Brockmann 1) = Alumina, Neutral, Brockmann 1, Standard Grade, ~ 150 mesh, Aldrich Chemical Co. [c] Al_2O_3 (Adsorption) = Alumina, Adsorption Grade, 80-200 mesh, Fisher Scietific Co. [d] Unactivated = Alumina was used directly from the bottle. [e] Activation temperature in parenthesis.

Table II-15. Colors of Acid Indicators Adsorbed on CCl_4 Modified Aluminas.

Indicators	Bromothymol blue	2,4-Dinitro aniline	4-Nitroaniline	4-Chloroaniline
Color change[a] Acidform→ Baseform	Y → G	Y → V	Y → O	Cl → P
pK_a	+7.2	+15.0	+18.4	+26.5
Modified Solids				
CCl_4/Al_2O_3 (Unactivated)[b] stirred at RT	G	Y	Y	Cl
CCl_4/Al_2O_3(100°C)[b] stirred at RT	G	Y	Y	Cl
CCl_4/Al_2O_3(175°C)[b] stirred at RT	Y	Y	Y	Cl
CCl_4/Al_2O_3(250°C)[b] stirred at RT	G	Y	Y	Cl
CCl_4/Al_2O_3(325°C)[b] stirred at RT	Y	Y	Y	Cl
CCl_4/Al_2O_3(400°C)[b] stirred at RT	Y	Y	Y	Cl
CCl_4/Al_2O_3 (Unactivated)[b] stirred at 70°C	G	Y	Y	Cl
CCl_4/Al_2O_3(100°C)[b] stirred at 70°C	G	Y	Y	P
CCl_4/Al_2O_3(175°C)[b] stirred at 70°C	G	Y	Y	Cl
CCl_4/Al_2O_3(250°C)[b] stirred at 70°C	G	Y	Y	Cl
CCl_4/Al_2O_3(325°C)[b] stirred at 70°C	G	Y	Y	Cl
CCl_4/Al_2O_3(400°C)[b] stirred at 70°C	G	Y	Y	Cl

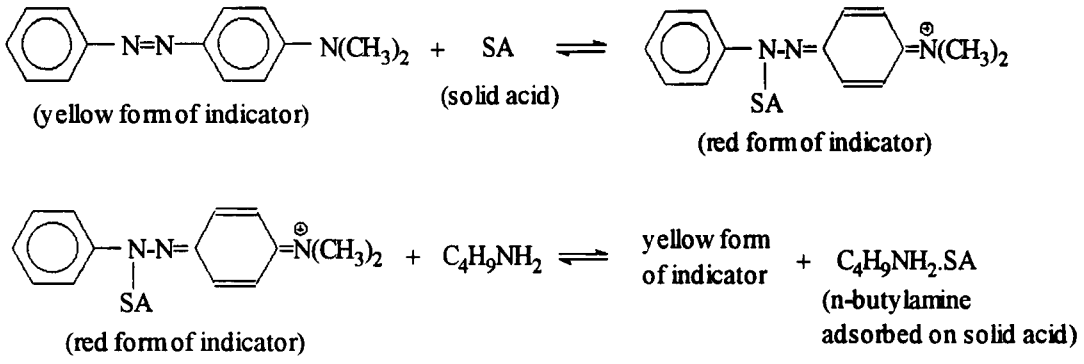
[a]G = green, Y = yellow, V = violet, O = orange, P = pink;
[b]Activation temperature in parenthesis.

Determination of the amount of acid on the solids and modified solids by amine titration method.

The amount of acid on a solid with a given H_o can be estimated by titrating it with a suitable base using an adsorbed base indicator with a pK_a value corresponding to H_o. Tamele was the first to use *n*-butylamine as titrant in these studies.[18] The method involves the titration of a solid acid suspended in benzene with *n*-butylamine using an indicator such as *p*-dimethylaminoazobenzene (pK_a = 3.3), for example. When this indicator is adsorbed on the solid acid, the yellow base form of the indicator will change to its red acid form if the solid is sufficiently acidic. The titres of *n*-butylamine needed to restore the yellow color therefore gives a measure of the number of acid sites on the surface. The titrating base should be more basic than the indicator used because the indicator must be displaced from the acid sites by the titrating base. If one used *p*-dimethylaminobenzene (pK_a = +3.3) as indicator, for example, the amount of *n*-butylamine required to change the color corresponds to the number of acid sites with H_o < +3.3. Thus, by using a series of indicators with different pK_a values, one can determine the number of acid sites with a variety of H_o values.

Both the Lewis acids and the Brønsted acids on the surface will react with *n*-butylamine (Scheme II-3).[18] Therefore, the titration method gives the sum of the number of Brønsted and Lewis sites. Other procedures are required to distinguish these two types of acids.[19]

Scheme II-3. Interaction of *p*-Dimethylaminobenzene with Solid Acid.



The procedure consisted of titrating *n*-butylamine of suitable normality against approximately 0.5 g of solid powder to which the appropriate indicator had been adsorbed. The color change on the solid indicates the end point of the titration. It should be remembered that for each solid type titration was done only with those indicators that showed a change from the base form of the indicator to the acid form. The results of the titration of *n*-butylamine with the dehydrated aluminas and the BBr_3 treated aluminas are shown in Table II-16 and II-17, respectively. The data from Table II-17 are also shown graphically in Figure II-12, page 142. The data collected in Tables II-16 and II-17 demonstrate that the dehydrated aluminas have significant concentrations of acid with widely varying H_0 values.

Table II-16. Moles of Acid Sites (at Different H_os) per Gram of Solid for a Variety of Aluminas (Activated and Unactivated).

Solid used	pK_a[b]	mole acid/gram solid[c]
Al_2O_3 (100°C)[a]	+4.8	1×10^{-5}
Al_2O_3 (100°C)[a]	+3.3	2×10^{-6}
Al_2O_3 (200°C)[a]	+0.8	6×10^{-6}
Al_2O_3 (200°C)[a]	-3.0	7×10^{-6}
Al_2O_3 (300°C)[a]	-3.0	5×10^{-6}
Al_2O_3 (400°C)[a]	+3.3	5×10^{-6}
Al_2O_3 (400°C)[a]	-3.0	2×10^{-6}

[a]Activation temperatures in parenthsis.

[b](Indicator/pK_a value): Methyl Red/ $pK_a = +4.8$; Methyl Yellow/$pK_a = +3.3$; Fast Garnet/$pK_a = +2.0$; Crystal Violet/$pK_a = +0.8$; Dicinnamalacetone/$pK_a = -3.0$; Anthraquinone/$pK_a = -8.2$.

[c]For each solid type, titration was done only with those indicators that showed a change from the base form of the indicator to the acid form.

Table II-17. Number of Moles of Acid Sites (at Different H_os) per Gram of Solid for a Variety of BBr_3/Al_2O_3 Complexes.

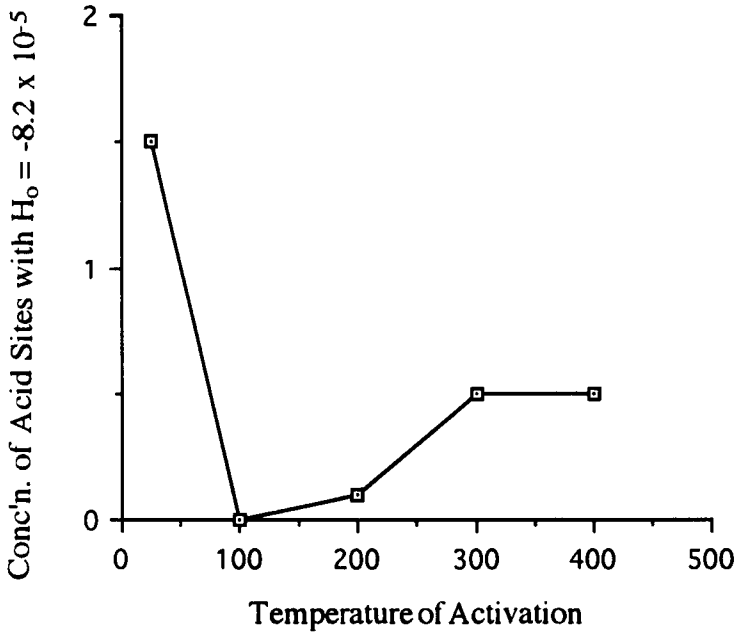
Solid used	pK_a[a]	mole acid/gram solid[b]
BBr_3/Al_2O_3 (Unactivated)[c]	+4.8	2.1×10^{-5}
BBr_3/Al_2O_3 (Unactivated)[c]	+3.3	1.5×10^{-5}
BBr_3/Al_2O_3 (Unactivated)[c]	+2.0	5.0×10^{-6}
BBr_3/Al_2O_3 (Unactivated)[c]	-3.0	8.0×10^{-6}
BBr_3/Al_2O_3 (Unactivated)[c]	-8.2	1.5×10^{-5}
BBr_3/Al_2O_3 (100°C)[c,d]	+4.8	1.5×10^{-5}
BBr_3/Al_2O_3 (100°C)[c,d]	+3.3	1.0×10^{-5}
BBr_3/Al_2O_3 (100°C)[c,d]	+2.0	1.0×10^{-5}
BBr_3/Al_2O_3 (100°C)[c,d]	-3.0	5.0×10^{-6}
BBr_3/Al_2O_3 (200°C)[c,d]	+2.0	2.0×10^{-6}
BBr_3/Al_2O_3 (200°C)[c,d]	+0.8	6.0×10^{-6}
BBr_3/Al_2O_3 (200°C)[c,d]	-3.0	7.0×10^{-6}
BBr_3/Al_2O_3 (200°C)[c,d]	-8.2	1.0×10^{-6}
BBr_3/Al_2O_3 (300°C)[c,d]	+4.8	1.0×10^{-5}
BBr_3/Al_2O_3 (300°C)[c,d]	+3.3	1.0×10^{-5}
BBr_3/Al_2O_3 (300°C)[c,d]	+2.0	1.0×10^{-5}
BBr_3/Al_2O_3 (300°C)[c,d]	-8.2	5.0×10^{-6}
BBr_3/Al_2O_3 (400°C)[c,d]	+4.8	1.8×10^{-5}
BBr_3/Al_2O_3 (400°C)[c,d]	+3.3	1.0×10^{-5}
BBr_3/Al_2O_3 (400°C)[c,d]	+2.0	1.0×10^{-5}
BBr_3/Al_2O_3 (400°C)[c,d]	-3.0	5.0×10^{-6}
BBr_3/Al_2O_3 (400°C)[c,d]	-8.2	5.0×10^{-6}

[a](Indicator/pK_a value): Methyl Red/ $pK_a = +4.8$; Methyl Yellow/$pK_a = +3.3$; Fast Garnet/$pK_a = +2.0$; Crystal Violet/$pK_a = +0.8$; Dicinnamalacetone/$pK_a = -3.0$; Anthraquinone/$pK_a = -8.2$.

[b]For each solid type, titration was done only with those indicators that showed a change from the base form of the indicator to the acid form. [c]Activation temperatures in parenthsis.

[d] Alumina was dehydrated for 4 hours at the indicated temperature before treatment with boron trihalide.

Figure II-12. Plots of Concentrations of Acid Sites at Various H_o versus Temperature of Activation for BBr_3/Al_2O_3.



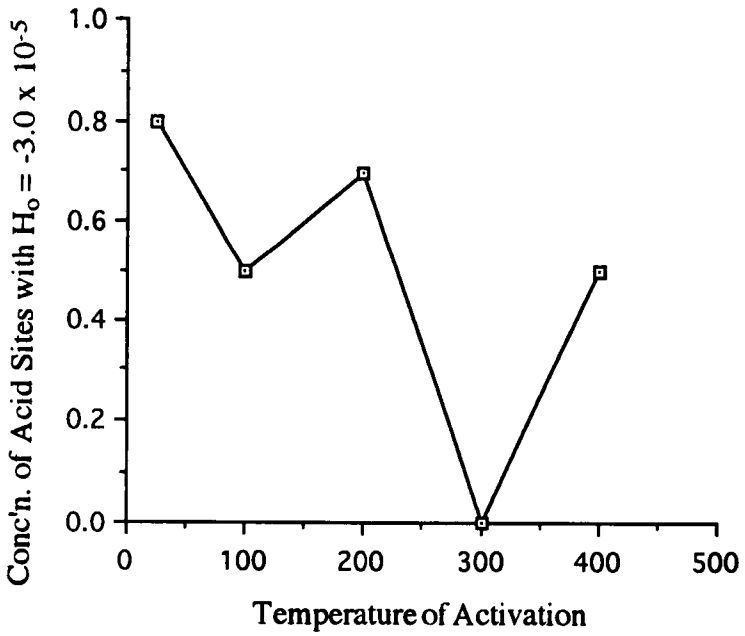
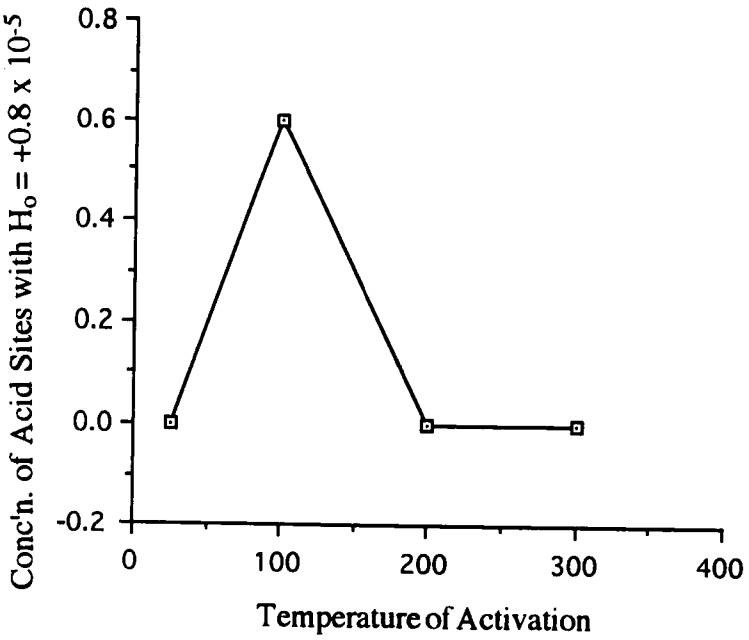


Figure II-12. Continued..



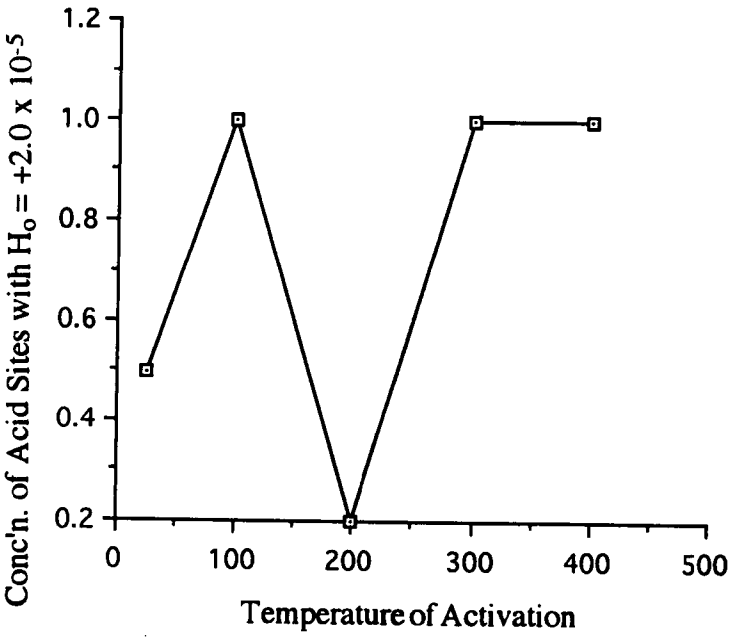
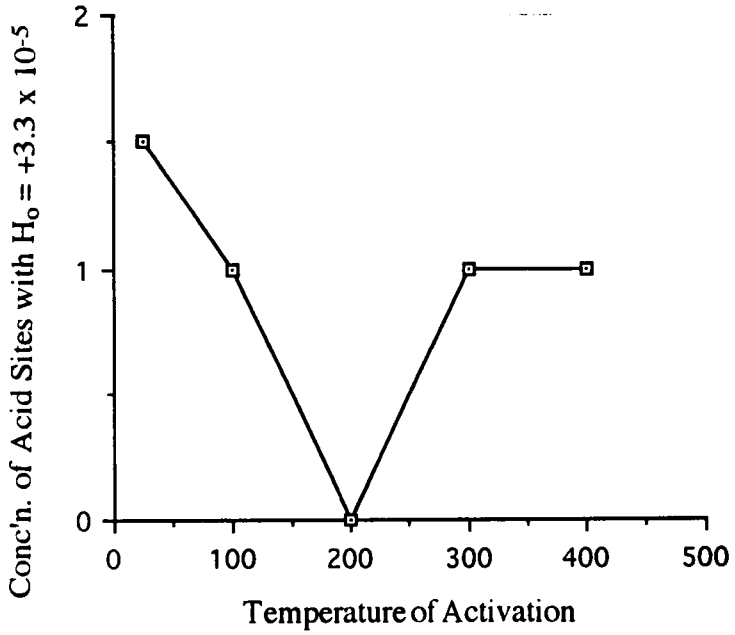
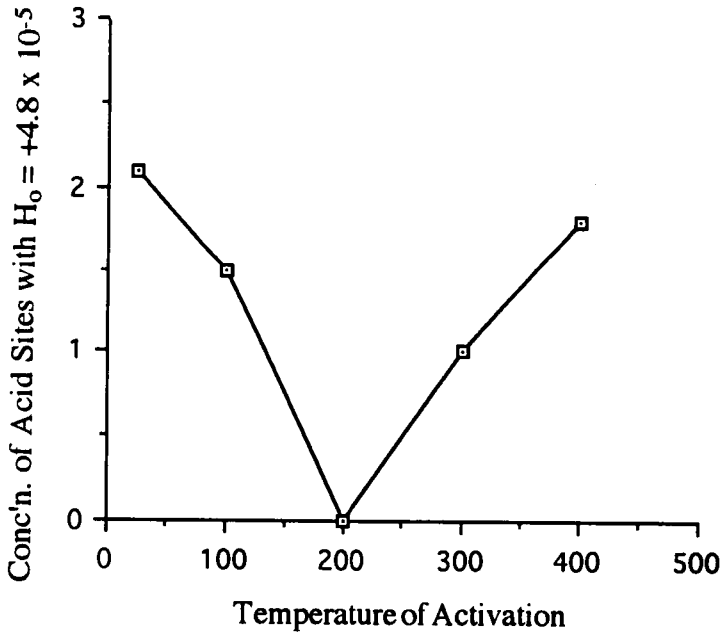


Figure II-12. Continued..





As one example from Table II-16 consider Al_2O_3(100°C); here there are 1 x 10^{-5} mole of acid per gram of solid at H_o = +4.8, and 2 x 10^{-6} mole of acid per gram of solid at H_o = +3.3. The concentration of acid on the other aluminas vary considerably. As can be seen from Figure II-12, the trends in concentration of acid for the various BBr_3/Al_2O_3(°C) also vary considerably. No attempt will be made here to rationalize this behavior.

C. Analysis of Modified Aluminas Using Solid State NMR Spectroscopy.

NMR spectroscopy has become an integral part of organic chemistry. Modern NMR techniques have revolutionized structural elucidation under a wide variety of conditions and in various phases. An area that has recently received considerable attention is the application of solid-state NMR (SS NMR) methods to the selective observation of surface systems of catalyic interest.[25,26,27]

A large portion of my research has involved using supported reagents such as sulfide and boron trihalides on alumina. Carbon tetrachloride treated alumina was also studied. Preliminary work was performed[19] in an attempt to analyze S^{-2}/Al_2O_3, BBr_3/Al_2O_3 and unactivated alumina by ^{27}Al, ^{11}B and ^{31}P CP/MAS NMR spectroscopy. Although the characterization of the surfaces of these solids requires more rigorous work, the results collected thus far deserves comment.

Results and Disscussion

^{27}Al NMR Spectra of Alumina and Modified Alumina.

The ^{27}Al chemical shift varies enormously depending on coordination number and attached ligands (Figure II-13). Generally, the chemical shift moves downfield as the Al passes from five-, through four-, to three-coordination with bound alkyl ligands. A similar progression is seen for the ionic or donor ligands; the chemical shift moves downfield in the order: six- > five- > four-coordinate aluminum. Because there are overlaps between the different shift regions, ^{27}Al shifts cannot be used on their own as diagnostic of the coordination number.[20]

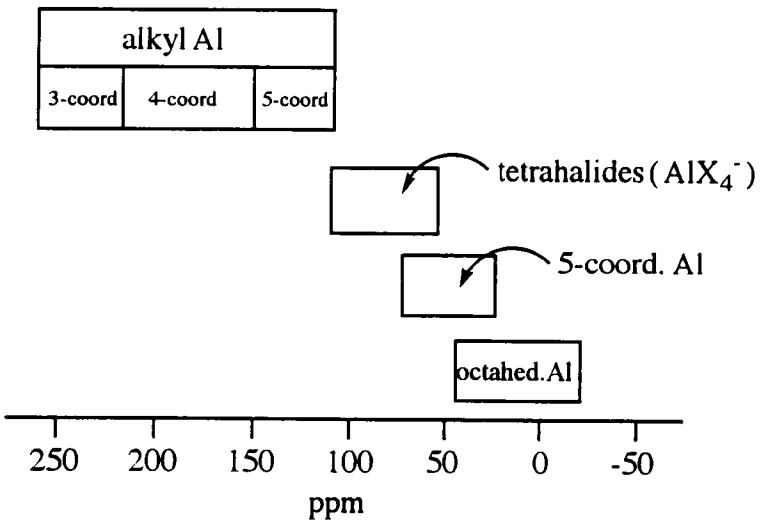


Figure II-13. Features of Aluminum-27 Chemical Shift Variations.[20]

Figure II-14 (a) shows the ^{27}Al MAS (magic angle spinning) SS NMR spectrum for unactivated γ-alumina (Brockmann Activity I). The standard was not added to the sample directly because it was feared that the standard would react with the sample. The spectrum has two resonances at ~ 165 and ~ 0 ppm which correspond to 4- and 8-coordinated aluminum, respectively.[20] The area ratio of 8- to 4-coordinated aluminum was ca. 4. For the sulfide impregnated alumina [2.99×10^{-3} moles/g Al_2O_3(100°C)] [Figure II-14 (b)] the ^{27}Al MAS NMR spectrum shows two resonances at ~ 155 and ~ 0 ppm, which also correspond to 4- and 8-coordinated surface aluminum.[20] The area ratio of 8- to 4-coordinated aluminum was ca. 4. Careful inspection of the spectra shows that there is a slight difference in the widths of the peaks for the γ-Al_2O_3 and S^{-2}/Al_2O_3. For the γ-alumina, the widths at half height (whh) at 0 ppm was 60 ppm, while the peak at 165 ppm also had a whh of 60 ppm. For the S^{-2}/Al_2O_3, the whh of the peak at ~ 0 ppm was about 30 ppm, while the peak at 150 ppm had a whh of about 100 ppm. The small differences in chemical shifts and line widths indicate that impregnation of sulfide on alumina has slightly modified the electron distribution around the aluminum nuclei. A detailed explanation for these differences will require a more detailed study, which is beyond the scope of this work.

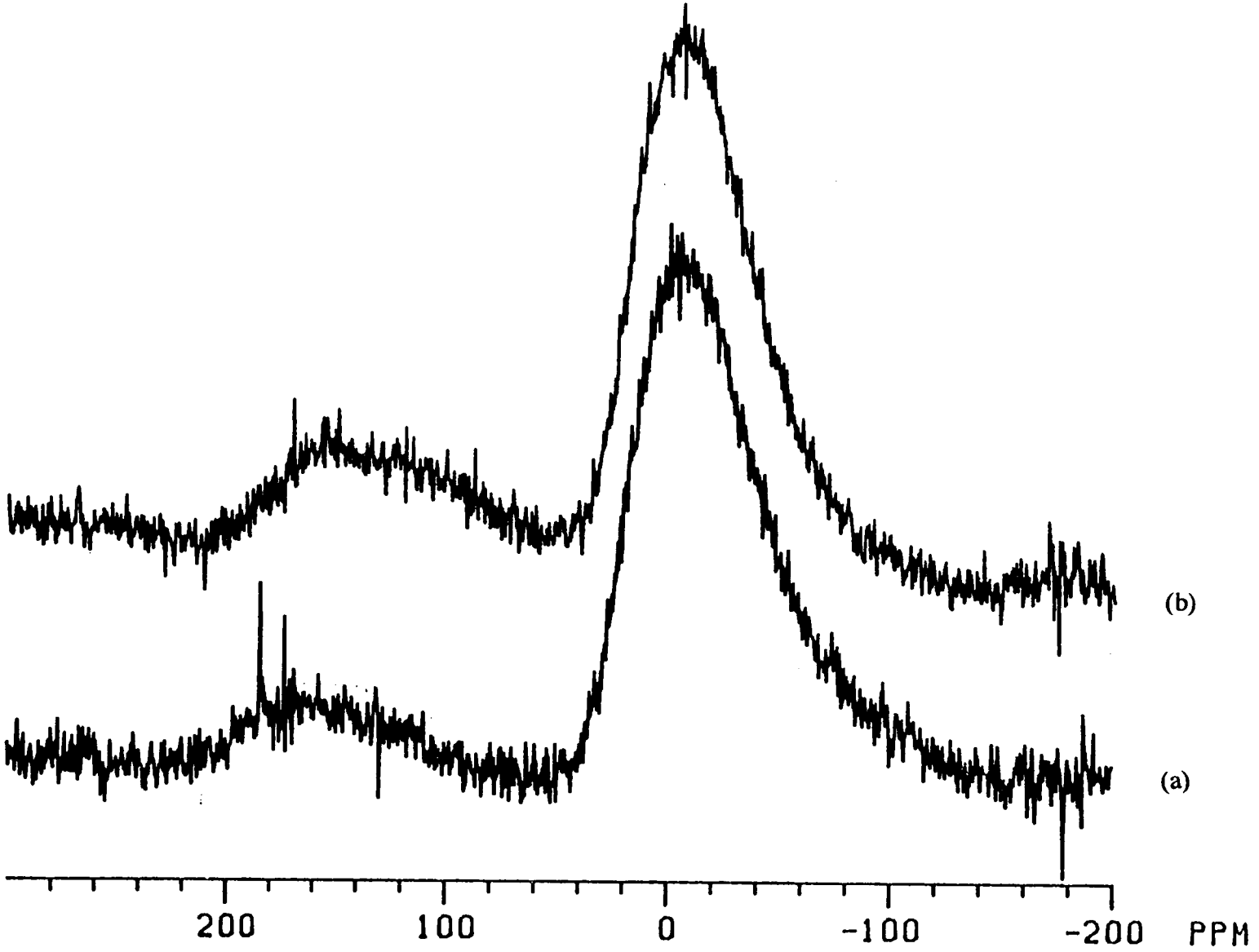


Figure II-14. ^{27}Al MAS SS NMR. (a) Alumina (unactivated) before Sulfide Impregnation. (b) Alumina after Impregnation of Sulfide.

^{27}Al NMR Spectra of γ-Alumina and Carbon Tetrachloride treated Alumina, CCl_4/Al_2O_3(400°C).

Figure II-15 shows ^{27}Al MAS NMR spectra for γ-alumina and CCl_4 treated alumina [CCl_4/Al_2O_3(400°C)]. The spectrum for γ-alumina has two resonances at ~165 ppm and ~0 ppm, corresponding to 4- and 8-coordinated aluminum, respectively. The area ratio of 8- and 4- coordinated aluminum was ca. 4. The whh of the peak at ~0 ppm was 60 ppm while the whh for the peak at 165 ppm was 60 ppm. For the CCl_4/Al_2O_3(400°C), the spectrum consists of two resonances at 130 ppm and -5 ppm. The whh of the peak at -5 ppm is 45 ppm, while the whh of the peak at 130 ppm is 60 ppm. The results imply that the electron distribution around the aluminum nuclei of the CCl_4 treated alumina is slightly different than the electron distribution around the aluminum nuclei of the γ-alumina itself.

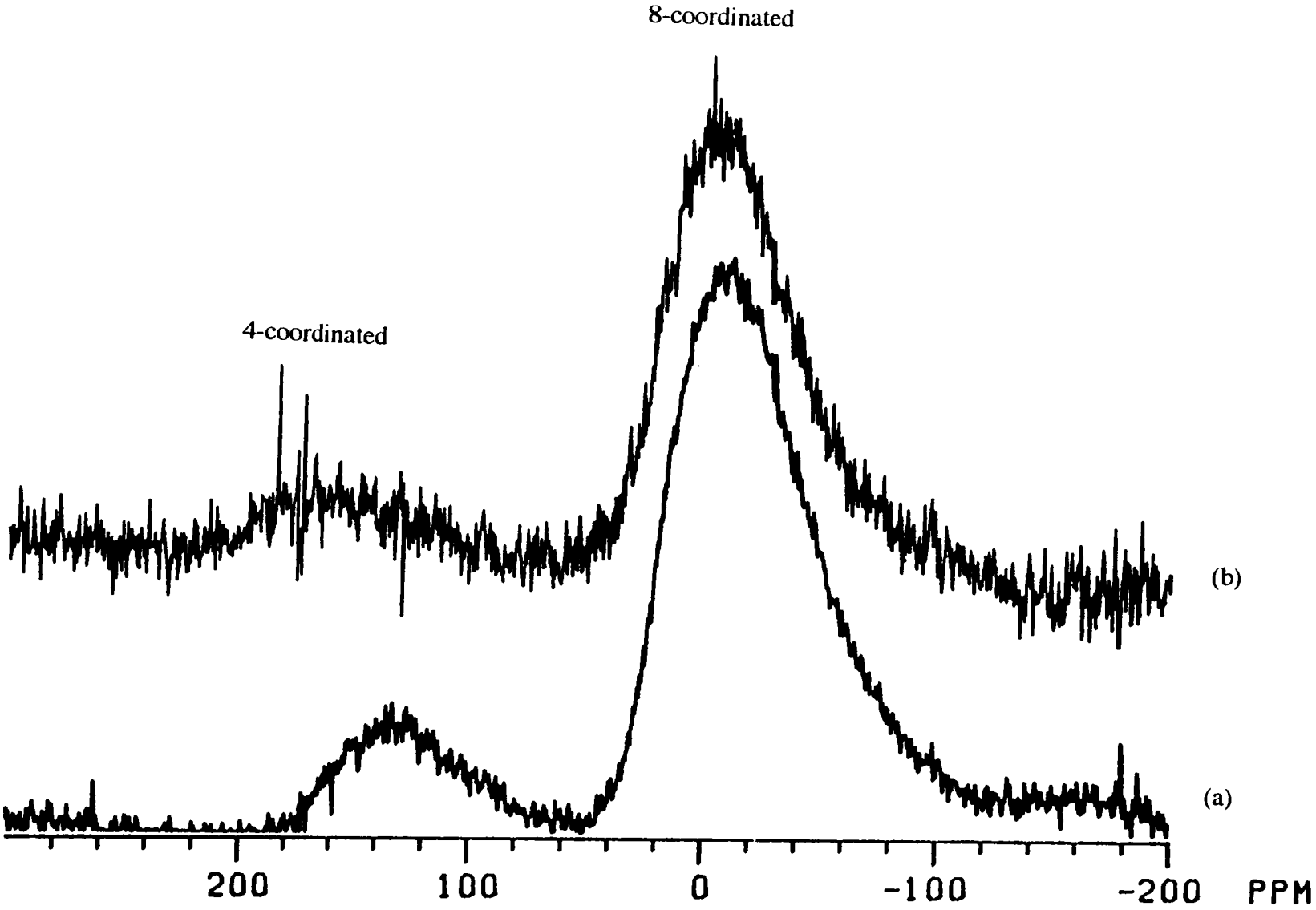


Figure II-15. ^{27}Al MAS SS NMR. (a) Alumina Treated with CCl_4 [CCl_4/Al_2O_3(400°C)]. (b) Alumina (unactivated) before Treatment with CCl_4.

^{27}Al NMR Spectra of γ-Alumina and BBr_3/Al_2O_3(400°C).

Figure II-16 shows the ^{27}Al MAS NMR spectrum for γ-alumina and BBr_3 impregnated alumina [BBr_3/Al_2O_3(400°C)]. As described previously, the spectrum for γ-alumina has two resonances at $\sim$165 ppm and $\sim$0 ppm, corresponding to 4- and 8-coordinated aluminum, respectively; the area ratio of 8- and 4- coordinated aluminum vs ca. 4. The whh of the peak at $\sim$0 ppm is 50 ppm while the whh for the peak at 165 ppm is 70 ppm. The BBr_3/Al_2O_3 has two resonances at 5 ppm and 100 ppm with the width of the peak at 5 ppm being 35 ppm and the whh of the peak at 100 ppm being 65 ppm. The results clearly show a greater difference in the whh for the 4-coordinated aluminum in the γ-alumina and BBr_3 treated alumina samples than the 8-coordinated aluminum. The differences in whh imply a change in the bonding characteristics of the surface 4-coordinate aluminum nuclei. Details on the exact type of bonding of the aluminum nuclei await further detailed NMR studies.

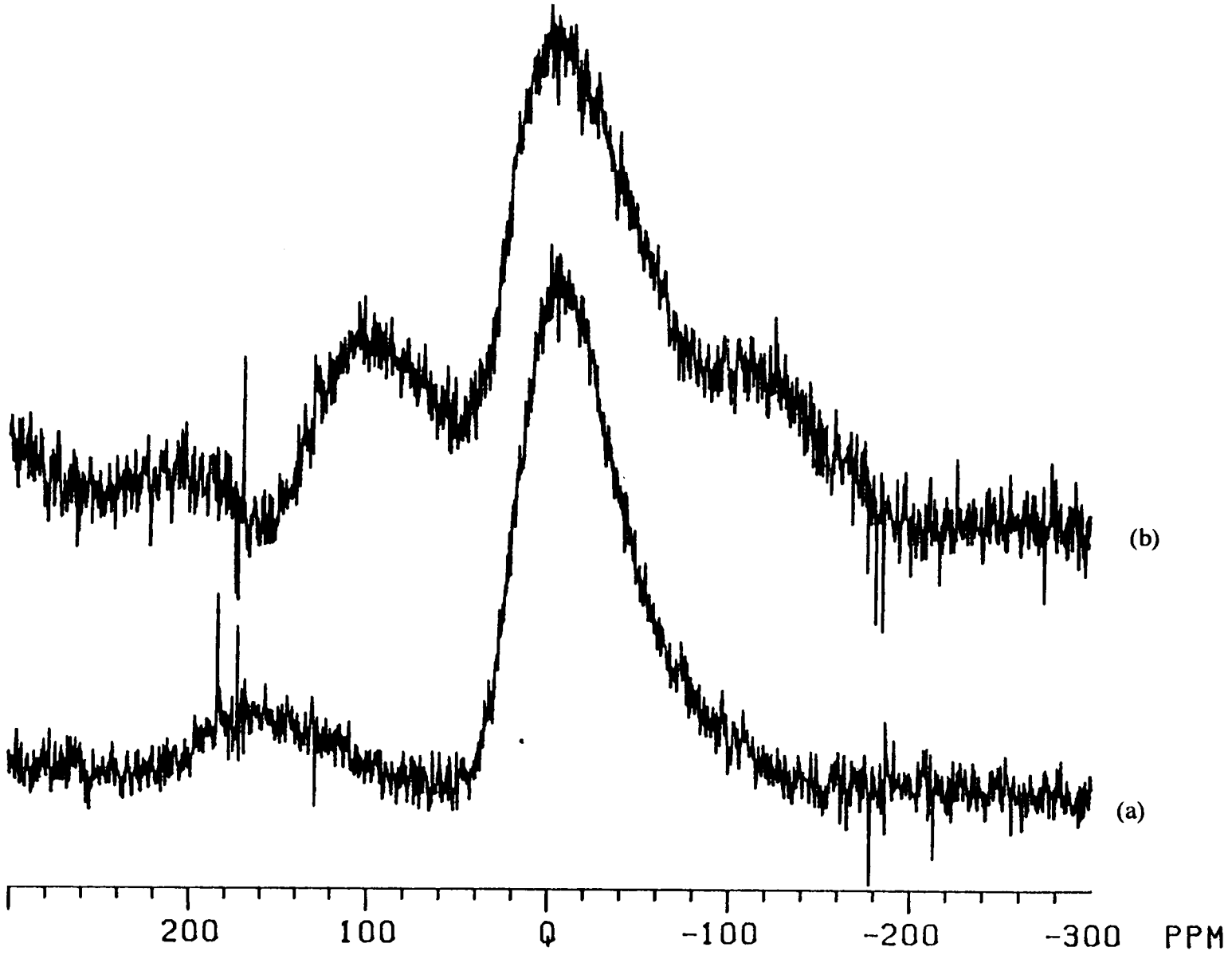


Figure II-16. ^{27}Al MAS SS NMR. (a) Alumina (unactivated) before Treatment of BBr_3. (b) Alumina after Impregnation of BBr_3 [BBr_3/Al_2O_3(400°C)].

^{11}B MAS NMR Spectra of BBr_3/Al_2O_3 .

Boron-11 is a nucleus which has been studied quite extensively by NMR spectroscopy.[21] Trigonal boron species displays a doublet line shape while tetrahedral boron species shows a singlet line shape (Figure II-17).[21]

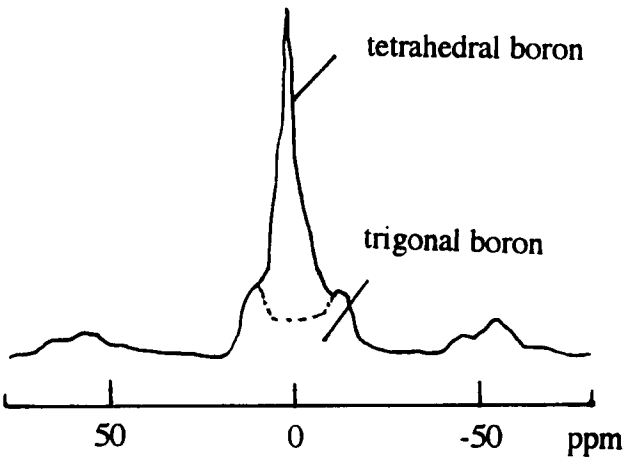


Figure II-17. ^{11}B NMR MAS Spectrum of $Na_2B_4O_6(OH)_2.3H_2O$.[21]

Figure II-18 shows the ^{11}B MAS SS NMR spectrum of BBr_3/Al_2O_3(400°C) (complexed to pyridine) with sodium tetraphenylborate as an internal standard. The resonance at 0.4 ppm corresponds to the internal standard while the peak at 5.5 ppm correspond to trigonal boron in the complex which coalescence to a singlet (typical of a tetrahedral boron signal after it is complexed to pyridine).[21] The peak at -38.8 ppm and 53.0 ppm are spinning side bands. This result shows that there are trigonal borons on BBr_3/Al_2O_3. Three possible structures for the boron species are shown in Figure II-19.

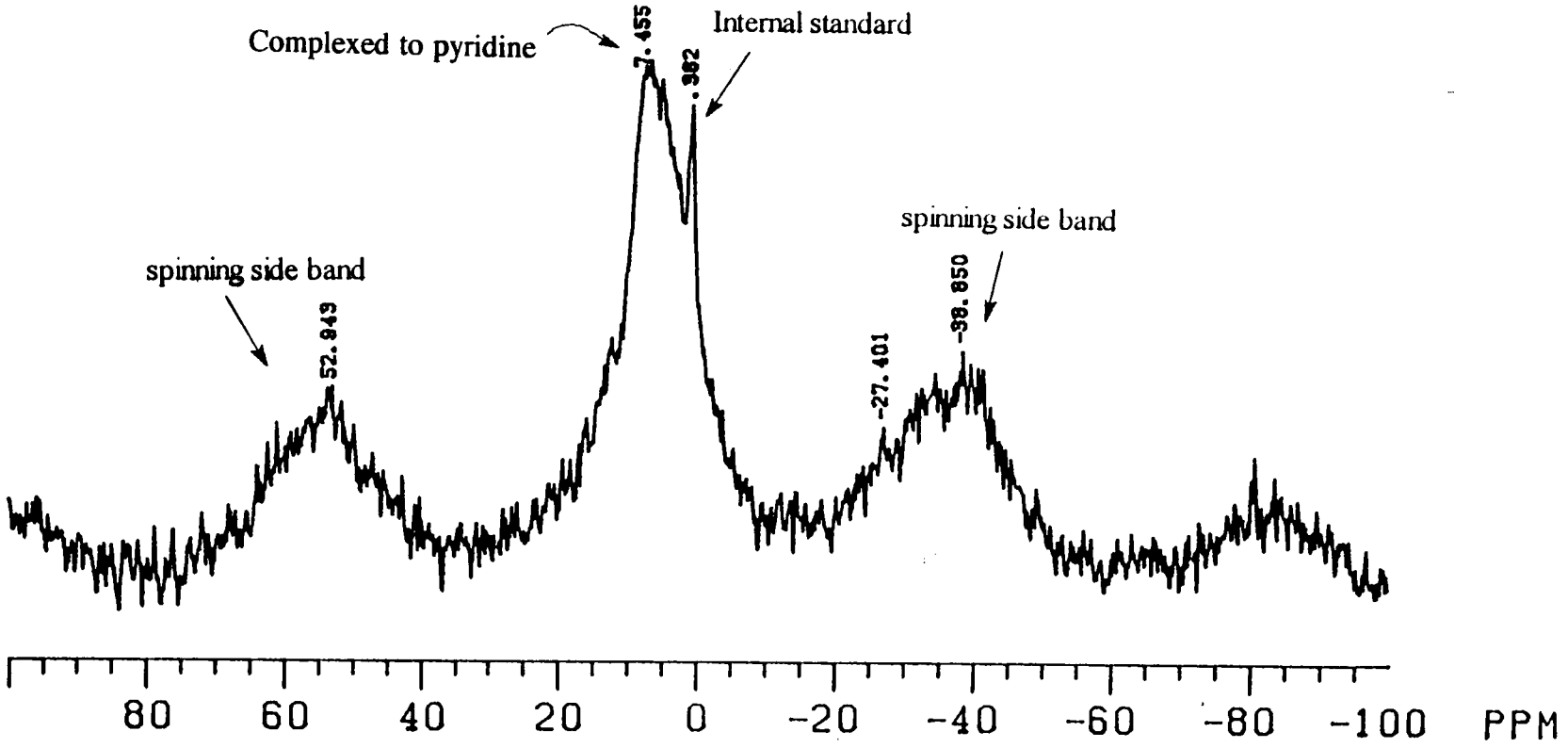


Figure II-18. ^{11}B MAS SS NMR Spectrum of BBr_3/Al_2O_3(400°C) (Complexed to Pyridine) with Sodium Tetraphenylborate as Internal Standard.

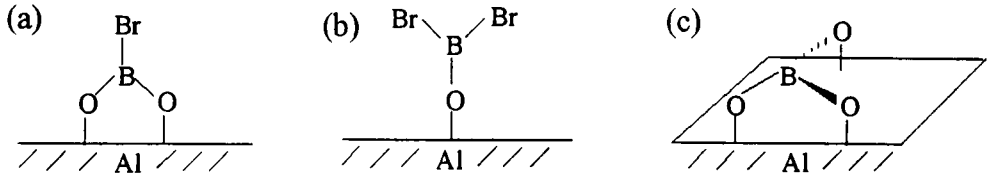


Figure II-19. Three Possible Structures for the $BBr_3/Al_2O_3(400°C)$. (a) Trigonal Boron Bonded to One Bromine Atom. (b) Trigonal Boron bonded to Two Bromine Atoms. (c) Trigonal Boron with No Br.

Although the boron in the $BBr_3/Al_2O_3(400°C)$ complex is trigonal, we cannot presently distinguish between the structures in Figure II-19 by NMR spectroscopy. However, the predominant structure is most likely the one shown in Figure 19 (a), based on the weight gain observed when BBr_3 is impregnated on alumina (page 179 , Part III).

^{31}P CP/MAS NMR Analysis of $BBr_3/Al_2O_3(400°C)$.

Preliminary experiments were also performed to determine the number of the Lewis acidic and Bronsted acidic sites by NMR titration using triethylphosphine oxide as the probe molecule. Addition of the tetramethyldiphosphine disulfide probe revealed 3 peaks. For further detail on this work, refer to the Dissertation of J. F. Green.

CHAPTER 3

EXPERIMENTAL SECTION

A. Materials

i. Solvents*,**

Cyclohexane

Benzene

Toluene

Carbon Tetrachloride

ii. Gases

Argon

iii. Reagents*,**

n-Butylamine

Bromothymol blue

2,4-Dinitroaniline

4-Nitroaniline

4-Chloroaniline

Methyl red

Methyl yellow

Fast garnet

Crystal violet

Dicinnamalacetone

Anthraquinone

m-Nitrochlorobenzene

Alumina, Brockmann Activity 1

Activated Alumina was prepared by the method described by Pagni, Kabalka, *et al.*[11]

* All the solvents and reagents were used as received from the supplier.

** Aldrich Chemical Company.

B. Experimental Methods

i. Analytical Method

The Solid State NMR spectra were acquired on a Nicolet NT-200 NMR spectrometer with a solid state probe made by Doty Scientific, Inc.

ii. Apparatus and Manipulation of Reagents

Reagents that are sensitive towards oxygen or moisture were transferred under dry argon atmosphere in a glove bag. All glassware, syringes and needles were oven-dried at 100°C for 6 hours, assembled hot and cooled under a slight positive pressure of argon using a pressure-regulated argon source with a mercury bubbler.

Air and moisture sensitive reagents were boron trihalide complexes (BX_3/Al_2O_3), dehydrated alumina, and the S^{-2}/Al_2O_3 complexes.

C. Experimental Procedures

i. Dehydration/Activation of Alumina

The procedure for dehydration of alumina is discussed in detail in the EXPERIMENTAL SECTION of Part I, page 86.

ii. Treatment/Adsorption of CCl_4 onto Alumina (unactivated and activated) - Slurried at Room Temperature. General Procedure A.

A known amount of alumina (activated or unactivated) was first added to the round bottomed flask followed by the addition of an excess amount of CCl_4 (50 mL). The reaction mixture was slurried for 20 hours at room temperature. After 20 hours, the unreacted CCl_4 was removed on a rotoevaporater at 55°C. The last traces of CCl_4 were then removed under vacuum (0.005 mm Hg) for another 20 hours at 40°C. The difference in weight between the alumina before and after treatment with CCl_4 at room temperature was recorded.

(a) Treatment of CCl_4 with Al_2O_3 (100°C) - slurried at room temperature.

18.750 grams of alumina that had been activated at 100°C under vacum for 20 hours [Al_2O_3(100°C)] was first added to a 250 mL round bottomed flask followed by the addition of an excess amount of CCl_4 (50 mL). The reaction mixture was slurried for 20 hours at room temperature. After 20 hours, the unreacted CCl_4 was removed on a rotoevaporator. The last traces of CCl_4 was then removed under vacuum (< 0.005 mm Hg) for another 20 hours at 40°C. The difference in weight of Al_2O_3(100°C) and the

weight of alumina treated with CCl_4 at room temperature was recorded. Initial weight of dehydrated alumina = 18.750 g; weight of alumina treated with CCl_4 = 19.042 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 0.292 g.

(b) Treatment of CCl_4 with Al_2O_3 (175°C) - slurried at room temperature.

The reaction procedure was identical to that described in general procedure A, page 158. However, Al_2O_3(175°C) was used in this slurry. Initial weight of dehydrated alumina = 17.553 g; weight of alumina treated with CCl_4 = 18.381 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 0.828 g.

(c) Treatment of CCl_4 with Al_2O_3 (250°C) - slurried at room temperature.

The reaction procedure was identical to that described in general procedure A, page 158. However, Al_2O_3(250°C) was used in this slurry. Initial weight of dehydrated alumina = 16.739 g; weight of alumina treated with CCl_4 = 18.128 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 1.389 g.

(d) Treatment of CCl_4 with Al_2O_3 (325°C) - slurried at room temperature.

The reaction procedure was identical to that described in general procedure A, page 158. However, Al_2O_3(325°C) was used in this slurry. Initial weight of dehydrated alumina = 15.659 g; weight of alumina treated with CCl_4 = 19.783 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 4.124 g.

(e) Treatment of CCl_4 with Al_2O_3 (400°C) - slurried at room temperature.

The reaction procedure was identical to that described in general procedure A, page 158. However, Al_2O_3(400°C) was used in this slurry. Initial weight of dehydrated alumina = 15.428 g; weight of alumina treated with CCl_4 = 20.209 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 4.781 g.

(f) Treatment of CCl_4 on Al_2O_3 (unactivated) - slurried at room temperature.

The reaction procedure was identical to that described in general procedure A, page 158. However, unactivated alumina Al_2O_3(unactivated) was used in this slurry. Initial weight of dehydrated alumina = 20.003 g; weight of alumina treated with CCl_4 = 19.832 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = -0.171 g.

iii. Calculations used to determine the number of moles of CCl_4 per gram of Al_2O_3 in reactions run at room temperature.

It is assumed that (i) one CCl_4 reacts for every O^{-2} on the surface and

(ii) weight gained is due to the addition of CCl_4.

(a) For Al_2O_3 dehydrated at 400°C.

Weight difference between the initial dehydrated alumina and alumina treated with CCl_4 at room temperature = +4.781 g.

$$4.781\ g\ \ x\ \ \frac{1\ mol\ CCl_4}{154\ g\ CCl_4} = 3.10\ x\ 10^{-2}\ mol\ CCl_4$$

The amount of dehydrated alumina used was 15.438 g.

Therefore, the number of mol of CCl_4 per gram of alumina is:

$$\frac{3.10\ g\ x\ 10^{-2}\ mol\ CCl_4}{15.438\ g\ Al_2O_3} = \frac{2.01\ x\ 10^{-3}\ mol\ CCl_4}{g\ Al_2O_3}$$

This corresponds to a concentration of 1.21 x 10^{21} CCl_4/g Al_2O_3, i.e.,

$$\frac{2.01\ x\ 10^{-3}\ mol\ CCl_4}{g\ Al_2O_3}\ x\ \frac{6.02\ x\ 10^{23}\ CCl_4}{mol\ CCl_4} = \frac{1.21\ x\ 10^{21}\ CCl_4}{g\ Al_2O_3}$$

(b) For Al_2O_3 dehydrated at 325°C.

Weight difference between the initial dehydrated alumina and alumina treated with CCl_4 at room temperature = +4.124 g.

$$4.124\ g\ \ x\ \ \frac{1\ mol\ CCl_4}{154\ g\ CCl_4} = 2.68\ x\ 10^{-2}\ mol\ CCl_4$$

The amount of dehydrated alumina used was 15.659 g.

Therefore, the number of mol of CCl_4 per gram of alumina is:

$$\frac{2.68\ g\ x\ 10^{-2}\ mol\ CCl_4}{15.659\ g\ Al_2O_3} = \frac{1.71\ x\ 10^{-3}\ mol\ CCl_4}{g\ Al_2O_3}$$

This corresponds to a concentration of 1.03 x 10^{21} CCl_4/g Al_2O_3, i.e.,

$$\frac{1.71\ x\ 10^{-3}\ mol\ CCl_4}{g\ Al_2O_3}\ x\ \frac{6.02\ x\ 10^{23}\ CCl_4}{mol\ CCl_4} = \frac{1.03\ x\ 10^{21}\ CCl_4}{g\ Al_2O_3}$$

(c) For Al_2O_3 dehydrated at 250°C.

Weight difference between the initial dehydrated alumina and alumina treated with CCl_4 at room temperature = +1.389 g.

$$1.389\ g\ \ x\ \frac{1\ mol\ CCl_4}{154\ g\ CCl_4} = 9.02\ x\ 10^{-3}\ molCCl_4$$

The amount of dehydrated alumina used was 16.739 g.

Therefore, the number of mol of CCl_4 per gram of alumina is:

$$\frac{9.02\ g\ x\ 10^{-3}\ mol\ CCl_4}{16.739\ g\ Al_2O_3} = \frac{5.39\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}$$

This corresponds to a concentration of 3.24 x 10^{20} CCl_4/g Al_2O_3, i.e.,

$$\frac{5.39\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}\ x\ \frac{6.02\ x\ 10^{23}\ CCl_4}{mol\ CCl_4} = \frac{3.24\ x\ 10^{20}\ CCl_4}{g\ Al_2O_3}$$

(d) For Al_2O_3 dehydrated at 175°C.

Weight difference between the initial dehydrated alumina and alumina treated with CCl_4 at room temperature = +0.828 g.

$$0.828\ g\ \ x\ \ \frac{1\ mol\ CCl_4}{154\ g\ CCl_4} = 5.38\ x\ 10^{-3}\ molCCl_4$$

The amount of dehydrated alumina used was 17.553 g.

Therefore, the number of mol of CCl_4 per gram of alumina is:

$$\frac{5.38\ g\ x\ 10^{-3}\ mol\ CCl_4}{17.553\ g\ Al_2O_3} = \frac{3.07\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}$$

This corresponds to a concentration of 1.40 x 10^{20} CCl_4/g Al_2O_3, i.e.,

$$\frac{3.07\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}\ x\ \frac{6.02\ x\ 10^{23}\ CCl_4}{mol\ CCl_4} = \frac{1.85\ x\ 10^{20}\ CCl_4}{g\ Al_2O_3}$$

(e) For Al_2O_3 dehydrated at 100°C.

Weight difference between the initial dehydrated alumina and alumina treated with CCl_4 at room temperature = +0.292 g.

$$0.292\ g\ \ x\ \ \frac{1\ mol\ CCl_4}{154\ g\ CCl_4} = 1.90\ x\ 10^{-3}\ mol\ CCl_4$$

The amount of dehydrated alumina used was 18.750 g.

Therefore, the number of mol of CCl_4 per gram of alumina is:

$$\frac{1.90\ g\ x\ 10^{-3}\ mol\ CCl_4}{18.750\ g\ Al_2O_3} = \frac{1.01\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}$$

This corresponds to a concentration of 6.09 x 10^{19} CCl_4/g Al_2O_3, i.e.,

$$\frac{1.01\ x\ 10^{-4}\ mol\ CCl_4}{g\ Al_2O_3}\ x\ \frac{6.02\ x\ 10^{23}\ CCl_4}{mol\ CCl_4} = \frac{6.09\ x\ 10^{19}\ CCl_4}{g\ Al_2O_3}$$

iv. Treatment/Adsorption of CCl_4 onto Alumina (unactivated and activated) - Slurried at 70°C. General Procedure B.

A known amount of alumina was first added into a 250 mL round bottom flask followed by the addition of an excess amount of CCl_4 (50.0 mL). The reaction mixture was slurried for 20 hours at 70°C, after which the unreacted CCl_4 was removed on a rotoevaporator at 55°C. The last traces of CCl_4 were then removed under vacuum (< 0.005 mm Hg) for 20 hours at 40°C. The difference in weight between the alumina and the weight of alumina treated with CCl_4 at room temperature was recorded.

(a) Treatment of CCl_4 with Al_2O_3 (100°C) - slurried at 70°C.

50 mL of CCl_4 was introduced into a 250 mL round bottom flask containing 20.003 g of alumina that had been activated at 100°C under vacuum for 20 hours [Al_2O_3(100°C)]. The reaction mixture was slurried for 20 hours at 70°C. After 20 hours, the unreacted CCl_4 was removed on a rotoevaporator at 55°C. The last traces of CCl_4 were then removed under vacuum (0.005 mm Hg) for 20 hours at 40°C. The

difference in weight of Al_2O_3(100°C) and the weight of alumina treated with CCl_4 at room temperature was recorded. Initial weight of dehydrated alumina = 20.003 g; weight of alumina treated with CCl_4 = 24.985 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 4.982 g.

(b) Treatment of CCl_4 with Al_2O_3 (175°C) - slurried at 70°C.

The reaction procedure was identical to that described in general procedure B, page 164. However, Al_2O_3(175°C) was used in this slurry. Initial weight of dehydrated alumina = 20.003 g; weight of alumina treated with CCl_4 = 24.821 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 4.818 g.

(c) Treatment of CCl_4 on Al_2O_3 (250°C) - slurried at 70°C.

The reaction procedure was identical to that described in general procedure B, page 164. However, Al_2O_3(250°C) was used in this slurry. Initial weight of dehydrated alumina = 20.005 g; weight of alumina treated with CCl_4 = 23.018 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 3.013 g.

(d) Treatment of CCl_4 with Al_2O_3 (325°C) - slurried at 70°C.

The reaction procedure was identical to that described in general procedure B, page 164. However, Al_2O_3(325°C) was used in this slurry. Initial weight of dehydrated alumina = 20.004 g. Weight of alumina treated with CCl_4 = 19.790 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = -0.214 g.

(e) Treatment of CCl_4 with Al_2O_3 (400°C) - slurried at 70°C.

The reaction procedure was identical to that described in general procedure B, page 164. However, Al_2O_3(400°C) was used in this slurry. Initial weight of dehydrated alumina = 20.003 g. Weight of alumina treated with CCl_4 = 20.191 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 0.188 g.

(f) Treatment of CCl_4 with Al_2O_3 (unactivated) - slurried at 70°C.

The reaction procedure was identical to that described in general procedure B, page 164. However, unactivated alumina Al_2O_3(unactivated) was used in this slurry. Initial weight of dehydrated alumina = 20.002 g; weight of alumina treated with CCl_4 = 20.823 g; weight difference between wt. of CCl_4/Al_2O_3 and initial wt. of dehydrated Al_2O_3 = 0.821 g.

v. <u>pH Determination of the Various CCl_4 Treated Aluminas.</u>

6.00 grams of the CCl_4 treated aluminas was added to a vial containing 10.0 mL of distilled water. The CCl_4/Al_2O_3-distilled water slurry was stirred at room temperature for 3 minutes using a magnetic stirrer and stirbar. The pH of the aqueous layer was then recorded using a pH meter.

vi. Measurement of the Acidity of Alumina and Modified Alumina.

(a) Determination of the pK_a of alumina and modified aluminas using basic indicators. General Procedure C.

The determination of the pK_a of the solid samples was done by noting the color change of the base indicators used. Approximately 0.2 mL of the solid sample in powder form was transferred to a vial. 2 mL of a 1% solution of the base indicator in cyclohexane was added. The mixture was stirred for 3 to 5 minutes using a stirbar and a magnetic stirrer to allow enough time for the adsorption of the indicator onto the solid to occur. Adsorption, if it occured at all, usually proceeded very rapidly and the color change, if any, was quite striking.

(b) Determination of the pK_a of alumina and modified aluminas using acidic indicators.

The procedure for the determination of the pK_a of solid samples using acidic indicators was identical to that described in the procedure C above, except benzene was used as the solvent.

vii. Determination of the Number of Acid Sites on the Solids and Modified Solids by the Amine Titration Method.

The solid sample (0.2 mL) was first transferred to a small vial containing 2 mL of 1% base indicator in cyclohexane. The mixture was shaken briefly until a color

change was noted. This mixture was then titrated with *n*-butylamine of suitable normality. The mixture was stirred with a small stirbar for 3 to 5 minutes for each drop of *n*-butylamine that was titrated. The titration was terminated when there was a change in color of the solid.

viii. Solid State NMR Measurements

The samples were packed into the NMR rotor in a glove bag under argon to minimize contamination with air. Spectra were acquired on a Nicolet NT-200 NMR spectrometer with a solid state probe made by Doty Scientific, Inc. The technique of magic-angle spinning (MAS) was employed for the SS NMR analysis. Typical spinning rates of 3 to 4 kHz were employed by using dry nitrogen as the drive gas. The recycle delay was typically 5.0 sec. The ^{27}Al MAS SS NMR spectra of the samples were obtained at a resonance frequency of 52.131 MHz. The ^{11}B MAS SS NMR spectra were obtained at a resonance frequency of 64.189 MHz.

ix. Preparation of BX_3/Al_2O_3 Complexes.

This may be found in Part III, page 217.

REFERENCES

1. Knözinger, Ratmasamy, *Catal. Rev.-Sci. Eng.* **1978**, *17 (1)*, 31-70.
2. Parlar, H.; Baumann, R. *Angew. Chem. Int. Ed. Engl.* **1981**, *20*, 1014.
4. Laszlo, P. *Preparative Chemistry Using Supported Reagents*, Academic Press, New York: **1987**.
5. Posner, G.H.; Oda, M. *Tetrahedron Lett.* **1981**, 5003-5006.
6. Hondrogiannis, G.; Pagni, R.M.; Kabalka, G.W.; Anosike, P.; Kurt, R. *Tetrahedron Lett.* **1990**, 31, 5433.
7. Neutral, Brockmann Activity I alumina, 80-200 mesh, Fisher Chemical Company.
8. The more reactants there are on the solid, the lower the endo : exo ratio becomes, even on unactivated solid.
9. (a) Boothe, R.; Dial, C.; Conway, R.; Pagni, R. M.; Kabalka, G. W. *Tetrahedron Lett.* **1986**, 2207.

   (b) Pagni, R. M.; Kabalka, G. W.; Boothe, R.; Gaetano, K.; Stewart, L. J. in *Physical Organic Chemistry 1986* ; Kobayashi, M. Ed.; Elsevier, Amsterdam: **1987**, p. 399.
10. Peri, J.B. *J. Phys. Chem.* 1965, 69, 220.
11. Gaetano, K.; Pagni, R. M.; Kabalka, G. W.; Birdwell, P.; Walsh, E.; True, J.; Underwood, M. *J. Org. Chem.* **1985**, *50*, 499.
12. Thomson, J.; Webb,G.; Winfield,J.M. *J. Mol. Cat.*. **1991**, *67*, 117-126.
13. Douglas, B.E.; McDaniel, D.H. *Concepts and Models of Organic Chemistry,* Blaisdell Pub. Co., New York: **1965**, 212.

14. Cotton, F. A.; Wilkinson, G. *Advanced Inorganic Chemistry*; 4th ed., Wiley, New York: 1980; p. 484.

15. Tanabe, K. *Solid Acids and Bases*; Academic Press, New York: **1970**, p. 14.

16. Mirodatos, C.; Barthomeuf, D. *J. Am Chem. Soc.* **1981**, 39.

17. Hammett, L.P.; Deyrup, A.J. *J. Am. Chem. Soc.* **1932**, 54, 2721.

18. Tamele, M. W. *Dis. Faraday Soc.* **1950**, *8*, 270.

19. Heindel, N. D.; Burns, H. D.; Honda, T. *The Chemistry of Radiopharmaceuticals*; Mason, New York: 1978.

20. Mason, Joan, *Multinuclear NMR*; Plenum Press: New York, 1987, p. 278.

21. Nöth, H.; Wrackmeyer, B. *Nucear Magnetic Resonance Spectroscopy of Boron Compounds*; Springer, Berlin: 1978.

22. Boothe, R.E. *Thesis*, Univ. of Tenn., Knoxville, **1986**.

23. Benesi, H. A. *J. Am. Chem. Soc.* **1956**, *78*, 5490.

24. Gordon, A. J.; Ford, R. A., *The Chemist's Companion*, Wiley Interscience Pub., New York: **1972**, 375.

25. (a) Morris, H. Douglas; Ellis, Paul D. *J. Am. Chem. Soc.* **1989**, *111*, 6045. (b) Major, P.D.; Ellis, P.D.; *J. Am. Chem. Soc.* **1987**, *109*, 1648. (c) Huggins, B.A.; Ellis, P.D. *J. Am. Chem. Soc.* **1992,** 114, 2098.

26. Sato, S.; Sodesawa, T.; Nozaki, F. *J. Mol. Cat.* **1991**, *66*, 343-355.

27. Maciel, G.E.; Baltusis, L.; Frye, J.S. *J. Am. Chem. Soc. 108*, 7119.

28. Thomas, C.L. *Catalytic Processes and Proven Catalysts*; Academic, New York: 1970.

29. Smith, G. C.; Chojnacki,T.P.; Dasgupta, S.R.; Iwatate, K.; Watters, K.L. *Inorg. Chem.*,**1975**, *14*, 1419 .

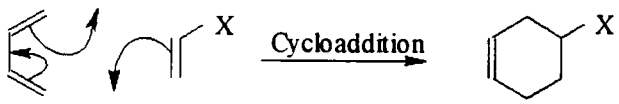
PART III

DIELS-ALDER REACTION ON BX_3/Al_2O_3 AND Al_2O_3

CHAPTER 1

INTRODUCTION

The Diels-Alder reaction is one of the fundamental and useful reactions in synthetic organic chemistry.[1,2] It is an important synthetic tool for the preparation of cyclic systems. The Diels-Alder reaction occurs between a conjugated diene (a 4π-electron system) and a compound containing a double bond (a 2π-electron system) called a dienophile (eq 1).

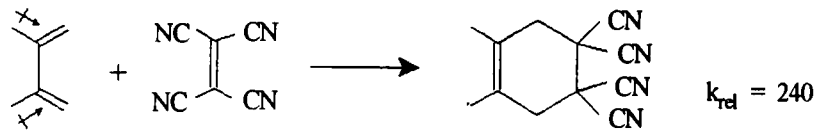


(1)

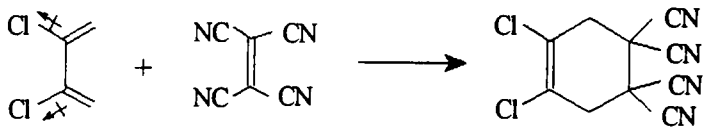
4 pi electrons 2 pi electrons

where X = electron withdrawing group

The dienophile usually consists of an alkene or an alkyne conjugated with one or more electron-withdrawing groups such as the cyano or nitro group. An electron withdrawing group conjugated to a double bond enhances the reactivity of the dienophile towards the diene. The presence of an electron-withdrawing group in the diene slows the reaction down, while an electron-donating substituent enhances it. For example, the relative rate constant for the reaction of 2,3-dimethyl-1,3-butadiene and tetracyanoethene (TCNE) is 240, while it is 10^{-3} for the reaction of 2,3-dichloro-1,3-butadiene with TCNE (eq 2 and eq 3).[3,4,5] There is clearly a difference in reaction rate, i.e., by a factor of 10^6, for the reaction of tetracyanoethene with dienes containing electron-donating (CH_3) and electron withdrawing (Cl) groups.



(2)



(3)

Relative reactivities of other dienophiles toward cyclopentadiene in the Diels-Alder reaction are shown in Table III-1. Two electron-withdrawing $COOCH_3$ groups can enhance or retard the reactivity of the dienophile, relative to the dienophile with one $COOCH_3$ group (methyl acrylate), depending on their orientation - cis in dimethyl maleate and trans in dimethyl fumarate.

Table III-1. Relative Reactivity Toward Cyclopentadiene in the Diels-Alder Reaction.[2]

Dienophile	Relative Rate
Dimethyl Fumarate	740
Dimethyl Maleate	6
Methyl Acrylate	12

The Diels-Alder reaction is thought to occur concertedly via a cyclic transition state[3] (Figure III-1). As a consequence of the concerted mechanism, the reaction is stereospecific. For example, reaction of isoprene with dimethyl maleate (a cis alkene) gives dimethyl *cis*-cyclohexene-5-methyl-1,2-dicarboxylate. The stereochemistry at the double bond of the dienophile is retained in the product (eq 4).

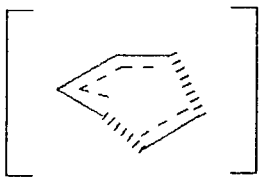
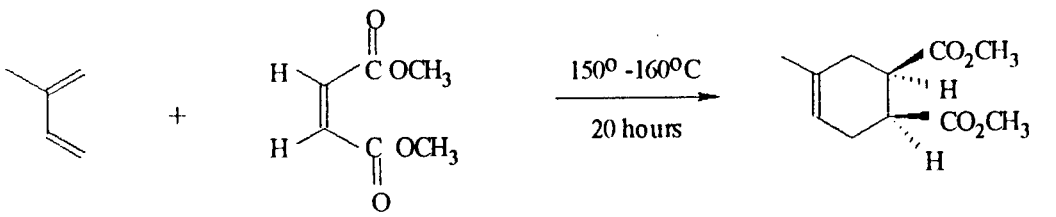


Figure III-1. Transition State of Diels-Alder Reaction.



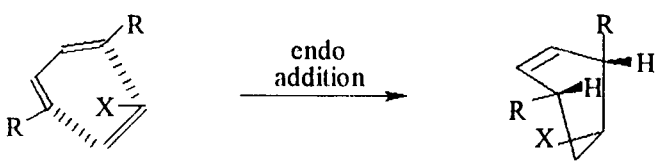
(4)

Isoprene

Dimethyl maleate

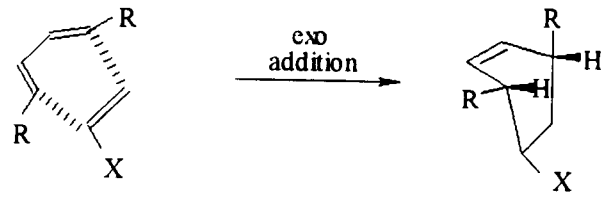
diethyl cis-cyclohexene
5-methyl-1,2-dicarboxylate

The Diels-Alder reaction is not only stereospecific with respect to the substituents on the reactants but also stereoselective with respect to the orientation of the starting materials relative to each other. Where it is appropriate, the Diels-Alder reaction usually proceeds with endo selectivity [Figure III-2 (a)] rather than exo selectivity [Figure III-2 (b)]. The stereochemical preference for the endo position is addressed by the Alder rule which states that, if two isomeric adducts are possible, the dienophile that has an unsaturated substituent oriented toward the newly formed cyclohexene double bond is the preferred product.[3,4,5] The two transition states are referred to as the endo and exo transition states for the endo-addition and exo-addition, respectively [Figure III-2 (a) and (b)].



endo transition state

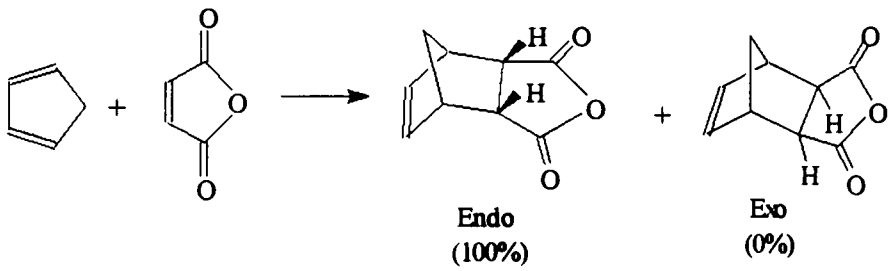
Figure III-2 (a). Transition State for Endo Addition.



exo transition state

Figure III-2 (b). Transition State for Exo Addition.

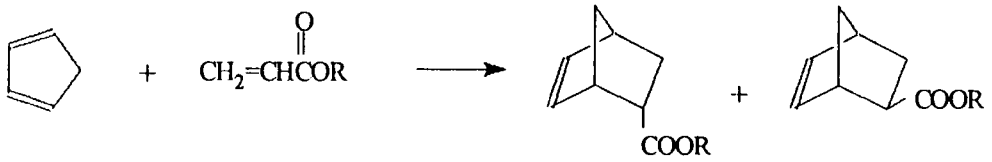
Consider the reaction of cyclopentadiene with maleic anhydride (eq 5); in agreement with the Alder rule, the reaction yields endo adduct exclusively, even though this is sterically more hindered than the exo adduct.



(5)

In research done by Grieco and coworkers, ethyl acrylate was reacted with cyclopentadiene in a 5.0 M solution of lithium perchlorate in diethyl ether to see what effect $LiClO_4$, a Lewis acid, had on the endo:exo ratio of the cycloadducts.[7] After 5 hours at ambient temperature and pressure, the reaction gave the cycloadducts in 93.0 % yield with an endo:exo ratio of 8:1 (eq 6). By comparison, a 3:1 ratio of adducts is formed in most solvents without lithium perchlorate. Parlar and Bauman,[8] on the other hand, observed that the reaction of cyclopentadiene and methyl acrylate yielded an approximately 30:1 ratio of endo to exo adducts on activated, neutral alumina; non-

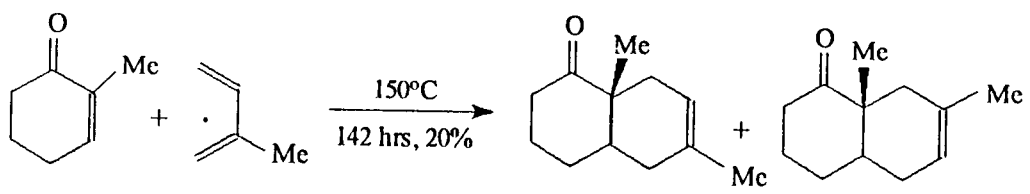
activated alumina also yielded a similar ratio of products (eq 6). Clearly, alumina can also function as a Lewis acid.



(6)

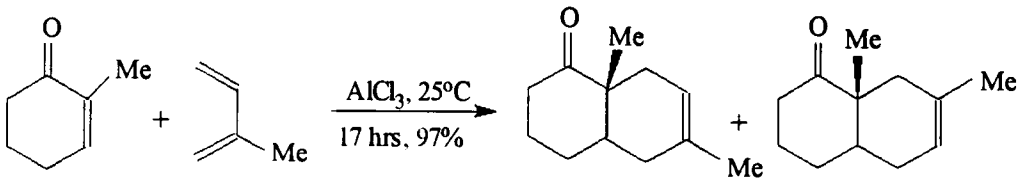
		(endo : exo)
R = Et :	5.0 M $LiClO_4/Et_2O$	8 : 1
R = Me :	Solution	3 : 1
R = Me :	Alumina	30 : 1

Acid catalysts have been found to increase the electrophilicity of the dienophile and, thus, increase the rate of Diels-Alder reaction.[2,7] In 1960, Yates and Eaton[9] first reported the remarkable rate acceleration in $AlCl_3$-catalysed the Diels-Alder reaction between anthracene and methyl acrylate, anthracene and 1,4-benzoquinone, and anthracene and dimethyl fumarate. Since then, Lewis acid catalyzed Diels-Alder reactions have received a lot of attention.[10,14,15,16,17,18] Cycloaddition reactions with unreactive dienophiles became more attractive to the synthetic organic chemist because the catalyzed reactions can be carried out under mild conditions. For example, the thermal cycloaddition of isoprene to 2-methyl-2-cyclohexenone gives a poor yield of the Diels-Alder adducts when the reaction is run at 150°C for 142 hours (eq 7). When the reaction is catalyzed by $AlCl_3$, however, the reaction proceeds at room temperature, and gives a much higher yield of adducts in a shorter period of time (eq 8).



(7)

(1.9 : 1)



(8)

(36 : 1)

As previously discussed in Part I, page 9, when alumina is heated at 400°C, it yields dehydrated alumina which has partially exposed aluminum cations which may catalyze the Diels-Alder reaction. Indeed, the Diels-Alder reactions of cyclopentadiene with methyl acrylate, dimethyl maleate and dimethyl fumarate are catalyzed by alumina.[8,9] In addition, activated alumina also catalyzes the isomerization of dimethyl maleate to dimethyl fumarate.[8,9] This isomerization does not occur, surprisingly, in a solution containing $AlCl_3$.[7]

Boron tribromide is a well-known Lewis acid which catalyzes the Diels-Alder reaction.[11] In order to see how a Lewis acid-modified alumina would influence the Diels-Alder reaction, BBr_3 was impregnated on alumina. As described in Part II, page 128, the boron tribromide impregnated alumina (BBr_3/Al_2O_3) is quite acidic, having an H_o of $\leq$ -13.2. The highly acidic BBr_3/Al_2O_3 complex should influence the reaction rate, product yield and stereoselectivity of Diels-Alder reactions. Experiments were run to see if some of these predictions are true.

In addition to studying how BBr_3/Al_2O_3 and related complexes affect the Diels-Alder reaction, the effect of BCl_3/Al_2O_3, BF_3/Al_2O_3, $SnCl_4/Al_2O_3$, $TiCl_4/Al_2O_3$ and activated and unactivated alumina on related reactions was also studied.

CHAPTER 2

RESULTS AND DISCUSSION

The first BBr_3/Al_2O_3 complex was prepared by slurrying 19.0 ml of a 1 M solution of BBr_3 in hexanes at room temperature for 30 minutes with 10.08 grams of alumina activated at 400°C for 4 hours under vacuum. After the hexane was removed under vacuum, the weight of the BBr_3/Al_2O_3(400°C) was recorded, and the BBr_3/Al_2O_3(400°C) complex then stored under argon. The weight increase of the BBr_3/Al_2O_3(400°C) due to the chemisorption of BBr_3 on alumina suggest that the presence of chemisorbed boron containing a free BBr bond, as shown in Figure III-3 (a) below.

Calculation for the weight gain of BBr_3/Al_2O_3(400°C) due to the chemisorption of BBr_3 on alumina:

The weight increase in Al_2O_3(400°C) after treatment with BBr_3 suggests that the adsorbed species contains a BBr bond. In order to arrive at this result, it is assumed that the Br^- formed in the BBr_3-Al_2O_3 reaction is lost as HBr and that all the BBr_3 reacted. The minor correction due to loss of H from the surface was not made. The calculation is shown below.

Wt. of Alumina used = 10.08 g

Wt. of Alumina + Flask = 267.74 g

Wt. of Alumina after activation at 400°C/4 hours + Flask = 266.67 g

Wt. of Alumina (activated) after treatment with BBr_3 in hexanes = 268.39 g

$\therefore$ Wt. Increase = 268.39g - 266.67g = 1.72 g, which corresponds to chemisorbed boron.

Amount of 1 M BBr_3 used = 19.0 mL (0.0190 mole).

The formula weight of B = 10.81. Therefore, 0.0190 mole B = 0.205 g.

The formula wt. of BBr = 90.72 g/mole. Therefore, 0.0190 mole BBr = 1.79 g.

The formula wt. of BBr_2 = 170.63 g/mole. Therefore, 0.0190 mole BBr_2 = 3.24 g.

The weight gain due to the adsorption of BBr_3 on alumina was 1.72 g. This suggests the presence of BBr on the surface rather than BBr_2 or B.

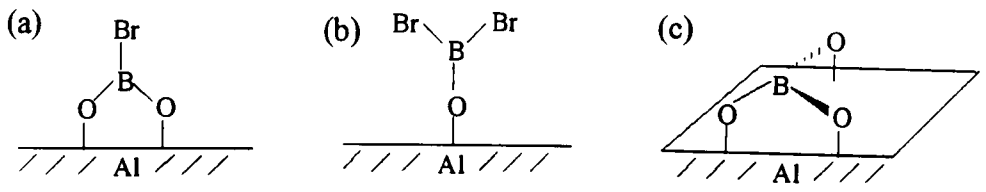


Figure III-3. Adsorption of BBr_3 on Alumina. (a) Trigonal Boron with a BBr Bond, (b) Trigonal Boron with BBr_2 Bond. (c) Trigonal Boron with No BBr Bond.

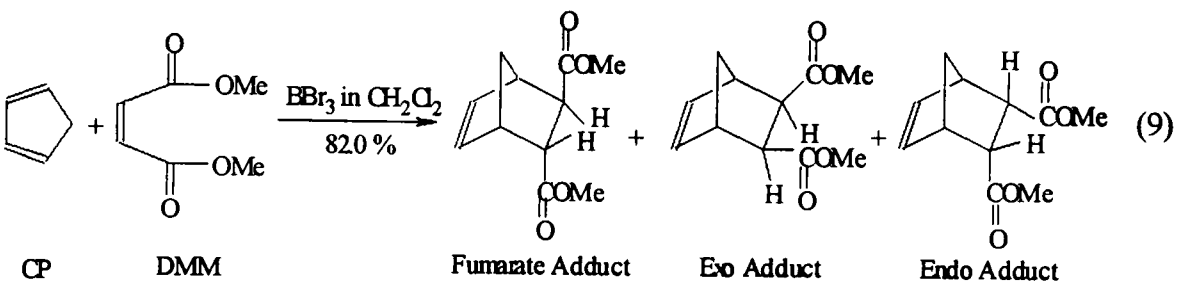
Furthermore, ^{11}B SS NMR spectroscopy (page 154, Part II) showed the complex to contain trigonal boron which is consistent with the structure shown in Figure III-3 (a). Acidity measurements showed the complex to be very acidic with an H_o of $\leq$ -13.2. Other BBr_3 complexes were prepared by adding BBr_3 to Al_2O_3 activated at 100°C, 200°C, 300°C and unactivated alumina. All these complexes also had H_o values of $\leq$ -13.2.

Because of the high acidity of the BBr_3/Al_2O_3, the solids may catalyze the Diels-

Alder reaction. An attempt was made to see if this is true. Cyclopentadiene (CP) was reacted with a series of dienophiles: dimethyl maleate (DMM), dimethyl fumarate (DMF), methyl acrylate (MA) and maleic anhydride (MAnh). Additionally, the reaction of isoprene (ISP) with MA was also examined. Competitive experiments were also carried out to see the effects that the BBr_3/Al_2O_3 complexes had on the relative reactivities of MA, DMM and DMF with CP. In order to have a basis for comparison, the relative reactivity of cyclopentadiene with MA, DMM and DMF on alumina itself was also measured.

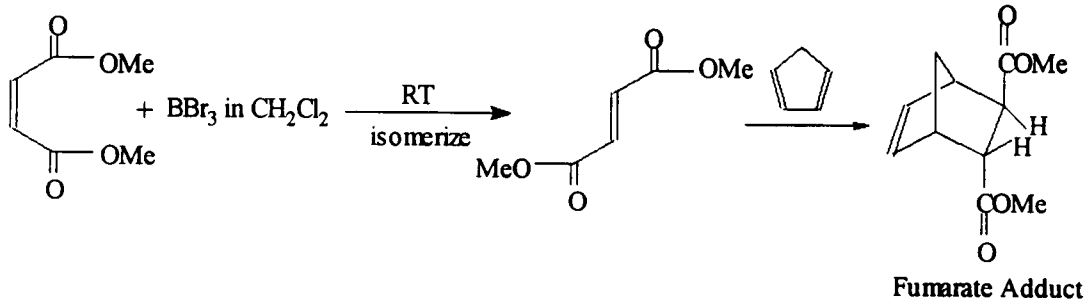
A. The Effect of BBr_3/Al_2O_3 Catalysis on the Diels-Alder Reactions between Cyclopentadiene and a Series of Dienophiles.

A reaction was first run between dimethyl maleate and cyclopentadiene in BBr_3/CH_2Cl_2 for 15 hours. The dienophile, DMM (6 mmol), was first added to BBr_3/CH_2Cl_2 and stirred for 20 minutes at room temperature under an argon atmosphere prior to the addition of CP (6 mmol) via a syringe. The reaction mixture was then stirred under argon for 15 hours at room temperature. Upon completion of the reaction, the product mixture was worked up and analyzed by the GC/MS. Analysis of the product mixture by GC/MS showed the presence of the fumarate, exo and endo adducts in a ratio of 37:1:62 (82.0% yield) (eq 9).



(9)

The formation of the fumarate adduct was unexpected and likely is due to the Diels-Alder reaction of CP with DMF formed by cis-trans isomerization of DMM (eq 10).



Fumarate Adduct (10)

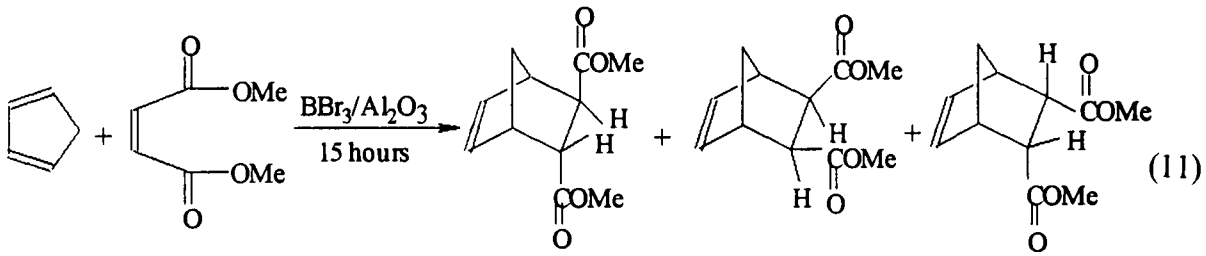
It was of interest to know if the surface-catalyzed reaction behaved similarly.

i. Reaction between Dimethyl Maleate and Cyclopentadiene on the BBr_3/Al_2O_3(400°C) Complex.

DMM (6 mmol) and CP (6 mmol) were treated with BBr_3/Al_2O_3 [10 mmol BBr_3/10 g Al_2O_3(400°C)] for 15 hours at room temperature under argon in the absence of solvent. The reaction was quenched with methanol and the product mixture analyzed by GC/MS. Three products were formed in this reaction: the fumarate adduct and the exo and endo DMM adducts in a 99:0:1 ratio, respectively, in a total yield of 89.0%. When the reaction was repeated in air, the adducts were formed in a 90:4:6 ratio (fumarate:exo:endo adduct), in a total yield of 88.0%. Exposure of the reaction to air did not alter the total yield or the adduct ratio significantly. Interestingly, the BBr_3/Al_2O_3 complex did not react violently with moisture in air, unlike BBr_3 in CH_2Cl_2.

In another experiment, the reaction was run on 10 mmol BBr_3/10 g Al_2O_3 (unactivated) under argon. The reaction afforded the fumarate, exo and endo adducts in

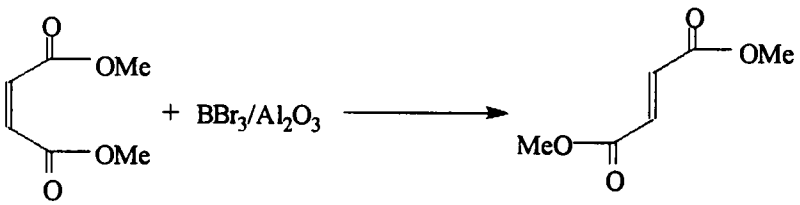
a 95:2:3 ratio, in 85.5 % yield. The results of this and the previously mentioned experiments are summarized in Equation 11. As in the reaction of CP with DMM in BBr_3/CH_2Cl_2, the fumarate adduct was also found on the BBr_3/Al_2O_3 complexes. DMM must have isomerized to DMF in the presence of the BBr_3/Al_2O_3 complex (eq 12) which then reacted with CP to form the fumarate adduct.



(11)

CP DMM Fumarate Adduct Exo Adduct Endo Adduct

BBr_3/Al_2O_3(400°C) under argon	(89.0%)	99	:	0	:	1
BBr_3/Al_2O_3(400°C) under air	(88.0%)	90	:	4	:	6
BBr_3/Al_2O_3(Unactivated) under argon	(85.5%)	95	:	2	:	3



(12)

The isomerization of DMM to DMF on BBr_3/Al_2O_3(400°C) and BBr_3/Al_2O_3(unactivated) is fast. When DMM was subjected to BBr_3/Al_2O_3 (unactivated) and BBr_3/Al_2O_3(400°C) complexes for 3 minutes, 90.0% of the dimethyl maleate had isomerized to dimethyl fumarate in both cases.

It is also possible that the fumarate adduct did not arise from dimethyl fumarate but by epimerization of the exo and endo DMM-CP adducts. This idea was tested by

subjecting pure endo and exo DMM adducts to the BBr_3/Al_2O_3(400°C) and BBr_3/Al_2O_3(unactivated) complexes for 5 minutes. Analysis of the product mixture did not reveal any fumarate adduct. It would appear that the fumarate adduct arises only from the reaction of CP with DMF, formed by isomerization of DMM to DMF.

An attempt was also made to determine how quickly these cycloaddition reactions occur. Reactions were run on the BBr_3/Al_2O_3(400°C) complex for 10 and 20 minutes. Analysis revealed that the reactions were completed in 10 minutes. The cycloaddition reaction that was run for 20 minutes afforded the fumarate, exo and endo adducts in a 99:0:1 ratio, respectively, in a total yield of 85.0%. Running the cycloaddition reaction for 10 minutes resulted in a 98:1:1 (fumarate:exo:endo) ratio, in a total yield of 85.0%. Table III-2 summarizes the results of the various reactions between DMM and CP on the BBr_3/Al_2O_3 complexes and BBr_3 in CH_2Cl_2.

Table III-2. Various Reactions between Dimethyl Maleate and Cyclopentadiene on the BBr_3/Al_2O_3 Complex and BBr_3 in CH_2Cl_2.

Entry	BBr_3/Al_2O_3 Complex	time/atmosphere[a]	Ratio[b]			% Yield[c]
			fum.	exo	endo	
1	BBr_3/Al_2O_3(400°)	15 hr/argon	99	0	1	89.0
2	BBr_3/Al_2O_3(400°)	15 hr/air	90	4	6	88.0
3	BBr_3/Al_2O_3(Unact'd)	15 hr/argon	95	2	3	85.5
4	BBr_3/Al_2O_3(400°)	20 min/argon	99	0	1	85.0
5	BBr_3/Al_2O_3(400°)	10 min/argon	98	1	1	85.0
6	BBr_3 in CH_2Cl_2	5 hr/argon	37	1	62	82.0

[a]All reactions were carried out at ambient temperature. [b] Established by the cut and weigh method of the areas under the peaks obtained from the respective GC/MS spectra. [c]Calculated by the cut and weigh method of the areas under the peaks of the GC/MS spectra, using of a known amount of hexadecane as the internal standard.

Because the formation of the fumarate adduct from the reaction between dimethyl maleate and cyclopentadiene on the BBr_3/Al_2O_3 complexes is intriguing, a study of how other boron trihalide/alumina complexes such as BCl_3/Al_2O_3 and BF_3/Al_2O_3 affected the cycloaddition between DMM and CP was made.

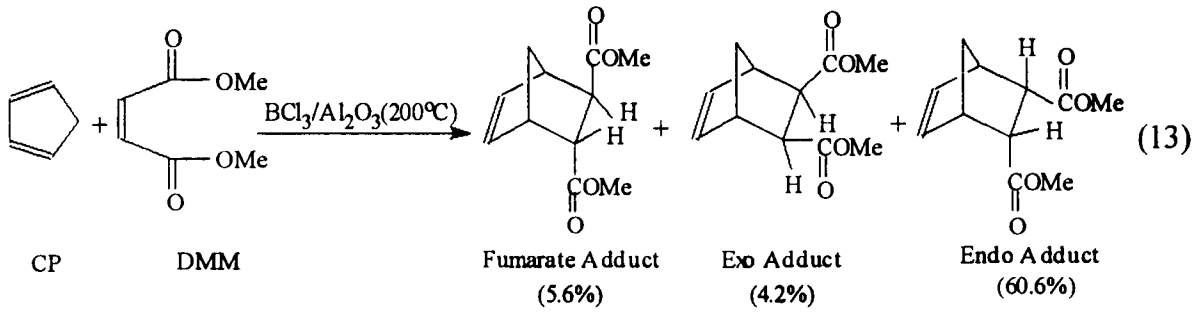
ii. Reaction between Dimethyl Maleate and Cyclopentadiene on the BCl_3/Al_2O_3 (200°C) Complex and in BCl_3/CH_2Cl_2.

(a) Preparation of BCl_3/Al_2O_3 (200°C).

The BCl_3/Al_2O_3 (200°C) complex was prepared by slurring at room temperature for 30 minutes 10 ml of 1 M solution of BCl_3 in hexanes and 10 grams of alumina that had been activated at 200°C under vacuum for 4 hours. After removing the solvent in vacuo, the BCl_3/Al_2O_3 (200°C) was stored under argon. Measurement of the acid strength of the BCl_3/Al_2O_3 (200°C) complex revealed an $-13.2 \leq H_o \leq -8.2$ (see page 128, Part II).

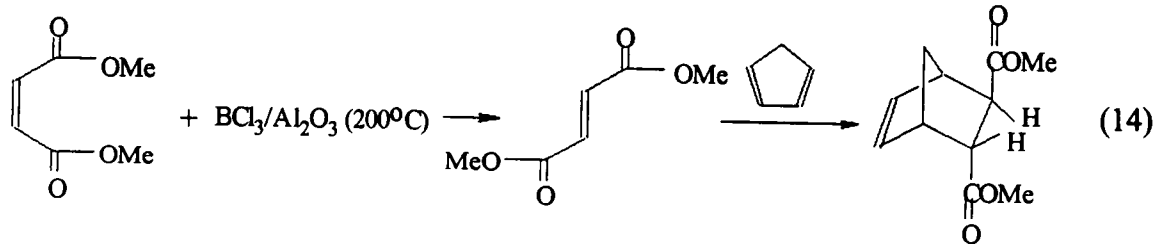
ii) The reaction between DMM and CP on the BCl_3/Al_2O_3(200°C) complex was carried out by treating DMM (6.0 mmol) and CP (6.0 mmol) with 10 grams of 10 mol BCl_3/10g Al_2O_3 (200°C) for 15 hours at room temperature under argon. Analysis of the product mixture by GC/MS revealed the formation of the fumarate, exo and endo adducts in a 8:6:86 ratio in 70.5% overall yield. As in the reaction of CP and DMM with BBr_3/Al_2O_3 (400°C), the fumarate adduct was also found in the reaction of CP and DMM with

BCl_3/Al_2O_3 (200°C). However, the amount of fumarate adduct formed on BCl_3/Al_2O_3 (200°C) was considerably less (eq 13).



(13)

In order to determine if DMM had isomerized to DMF on BCl_3/Al_2O_3 (200°C), DMM was subjected to the complex for 15 minutes at room temperature under argon. Only 5.0% of the DMM had isomerized to DMF under these conditions, compared to 90% isomerization in 3 minutes in the presence of BBr_3/Al_2O_3 complexes. The fumarate adduct generated in the cycloaddition reaction of DMM and CP on the BCl_3/Al_2O_3 (200°C) was probably formed in the same manner as on BBr_3/Al_2O_3 (400°C) (eq 14).



(14)

Fumarate Adduct

An experiment was also carried out by reacting DMM and CP with BCl_3 in CH_2Cl_2 for 15 hours. The results were similar to those observed on BCl_3/Al_2O_3 (200°C). The fumarate, exo and endo adducts were formed in a 13:9:78 ratio in 75.0% overall yield Table III-3.

Table III-3. Reaction between Dimethyl Maleate and Cyclopentadiene on the BCl_3/Al_2O_3 (200°C) and the BCl_3 in CH_2Cl_2.

Entry		time/atmosphere[a]	Ratio[b] fum exo endo	% Yield[c]
1	BCl_3/Al_2O_3 200°C	15 hr/argon	8 6 86	70.5
2	BCl_3 in CH_2Cl_2	15 hr/argon	13 9 78	75.0

[a]All reactions were carried out at ambient temperature. [b] Established by the cut and weigh method of the areas under the peaks obtained from the respective GC/MS spectra. [c]Calculated by the cut and weigh method of the areas under the peaks of the GC/MS spectra, using of a known amount of hexadecane as the internal standard.

iii. Reaction between Dimethyl Maleate and Cyclopentadiene on the BF_3/Al_2O_3(400°C) Complex.

(a) Preparation of BF_3/Al_2O_3(400°C)

The BF_3/Al_2O_3(400°C) complex was prepared by slurring at room temperature for 30 minutes 10 ml of 1 M solution of BF_3-etherate with 10 grams of alumina that had been activated at 400°C under vacuum for 4 hours. After removal of ether under vacuum, the BF_3/Al_2O_3(400°C) was stored under argon. Measurement of the acid strength of the BF_3/Al_2O_3(400°C) complex revealed the solid to have an $-8.2 \leq H_o \leq -3.0$ value. The BF_3/Al_2O_3(400°C) is acidic, but not as acidic as the BCl_3/Al_2O_3(200°C) complex or the BBr_3/Al_2O_3(400°) complex.

(b) The reaction between dimethyl maleate and cyclopentadiene on the BF_3/Al_2O_3(400°C) complex was carried out as follows. DMM (6.0 mmol) and CP (6 mmol) were added, via a syringe to 10 grams of 10 mmole BF_3/10 g Al_2O_3(400°C) and

the reaction mixture stirred at room temperature under argon for 15 hours. After workup, the product mixture was analyzed by CG/MS, which revealed the presence of only the exo and endo adducts in a ratio of 10:90 with the total yield of adduct being 75.2%. DMM was subjected to the BF_3/Al_2O_3(400°C) for 15 minutes at room temperature as described previously; no DMF was formed. Clearly, the rate of isomerization is faster on BBr_3/Al_2O_3 than on BCl_3/Al_2O_3, and no isomerization occurred on the BF_3/Al_2O_3. The trend of the rate of isomerization is similar to the trend found in the acidity of these complexes, where the H_o of $BBr_3/Al_2O_3 < BCl_3/Al_2O_3 < BF_3/Al_2O_3$ (i.e. $\leq$-13.2, $\leq$-8.2 and $\leq$-3.0, respectively). The trend is also identical to that found for the acidity of these boron trihalides themselves, where $BBr_3 > BCl_3 > BF_3$.[11] A plausible explanation for the formation of the DMF from DMM is as follows: A bond is formed between the lone pair of electrons on the carbonyl oxygen of DMM and the empty orbital of boron (Fig. III-4). The result is a carbocation, Fig. III-4(b), in which the C-C double bond is considerably weakened, thus permitting rotation about the bond to form DMF.

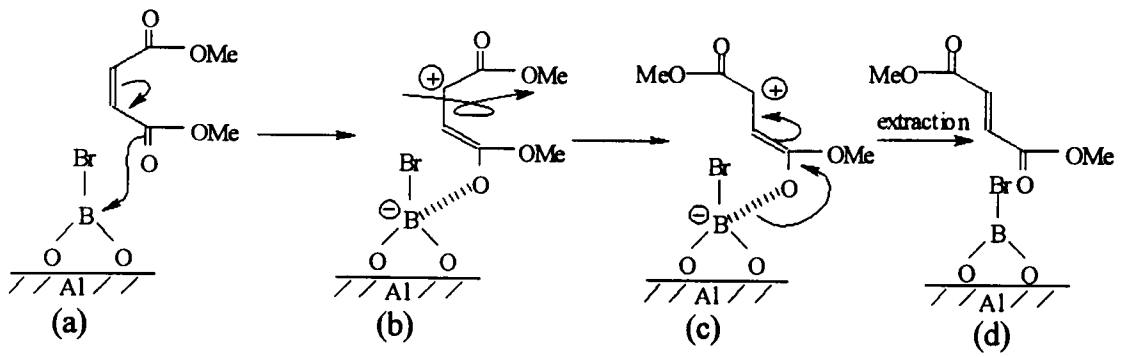
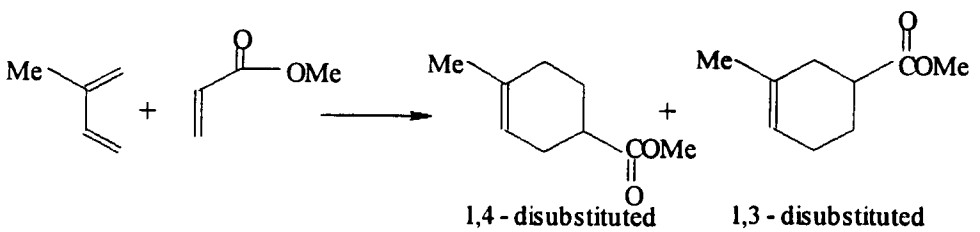


Figure III-4. Isomerization of DMM to DMF in the Presence of BBr_3/Al_2O_3.

Because the behavior of DMM and CP on BX_3/Al_2O_3 (X = Br, Cl, F) proved to be so intriguing, a few other Diels-Alder reactions were examined. The cycloadditon reactions of methyl acrylate with isoprene and maleic anhydride with cyclopentadiene were chosen because both reactions can yield two adducts.

iv. Reaction of Methyl Acrylate and Isoprene on the BBr_3/Al_2O_3(400°) Complex.

The Diels-Alder reaction of methyl acrylate and isoprene was first performed in solution. When methyl acrylate (0.01 mole) was reacted neat with isoprene (0.01 mole) at ambient temperature for 4 hours under argon, the 1,3- and 1,4-disubstituted adducts were formed in a ratio of 15:85 with a total yield of 52.3% (eq 15). The 15:85 ratio is consistent with a literature value.[12] When the reaction between methyl acrylate and isoprene was repeated in the presence of BBr_3/Al_2O_3(400°C) complex at room temperature for 4 hours, the 1,3-disubstituted and 1,4-disubstituted adducts were formed in a 10:90 ratio in an overall yield of 60.2%.



(15)

	1,4 - disubstituted		1,3 - disubstituted	
without BBr_3/Al_2O_3	84	:	16	(52.3%)
with BBr_3/Al_2O_3	90	:	10	(60.2%)

The BBr_3/Al_2O_3(400°C) complex not only had a modest effect on the total yield of the reaction, but also the selectivity of the 1,4-disubstituted to 1,3-disubstituted

adducts as well. At present it is not possible to provide a consice explanation for the effect of $BBr_3/Al_2O_3(400°C)$ on the total yield and the selectivity just described. However,it seems plausible that this effect on the yield and the selectivity is due to the catalytic sites on the surface of the $BBr_3/Al_2O_3(400°C)$.

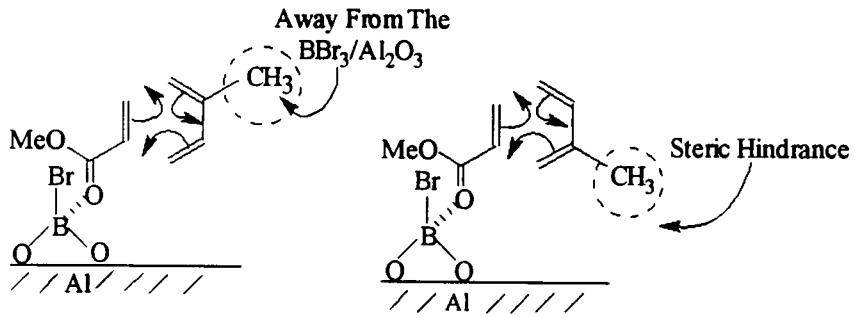
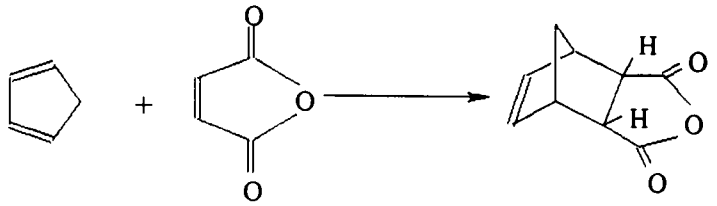


Figure III-5. Cycloaddition of MA and ISP in the Presence of BBr_3/Al_2O_3.

When MA reacts with ISP in the presence of the $BBr_3/Al_2O_3(400°C)$ complex, it prefers to do so in such a way that the CH_3 group of the ISP is as far away from the COOMe group of the MA, which favors the para product. Such an effect is not observed in the solution.

v. Reaction of Maleic Anhydride (MAnh) and Cyclopentadiene on the $BBr_3/Al_2O_3(400°C)$.

The Diels-Alder reaction between MAnh and CP was first performed in solution. The cycloaddition reaction, run in benzene at ambient temperature for 4 hours under argon, yielded the endo adduct exclusively (90.0% yield). (eq 16).

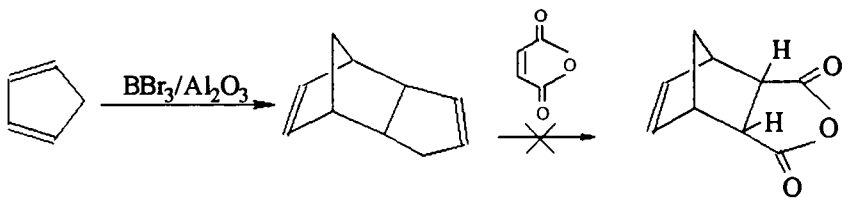


(16)

In benzene 90.0%
In BBr_3/Al_2O_3 35.0%

One might have expected that the use of BBr_3/Al_2O_3(400°C) would catalyse the reaction of MAnh and CP to give a higher yield than when the reaction was run in benzene. However, this turned out not to be the case. When the reaction of MAnh and CP was repeated in the presence of the BBr_3/Al_2O_3(400°C) at room temperature for 4 hours, the same cycloadduct was formed, but only in 35.0%. Further work will be required to explain the decrease in the yield of the MAnh-CP adduct.

In another study, the order of addition of the reactants to the alumina was reversed, i.e., the cyclopentadiene was first added to the BBr_3/Al_2O_3(400°C) and, after stirring for 5 minutes at room temperature under argon, the MAnh was added. No MAnh-CP adduct was produced after a 4 hour reaction time (eq 17). Most likely, the CP dimerized on the solid before the addition of the maleic anhydride.



(17)

Endo Adduct Not Observed

Thus far, the research has focused primarily on the cycloaddition reactions between dimethyl maleate and cyclopentadiene on the various boron trihalide/alumina

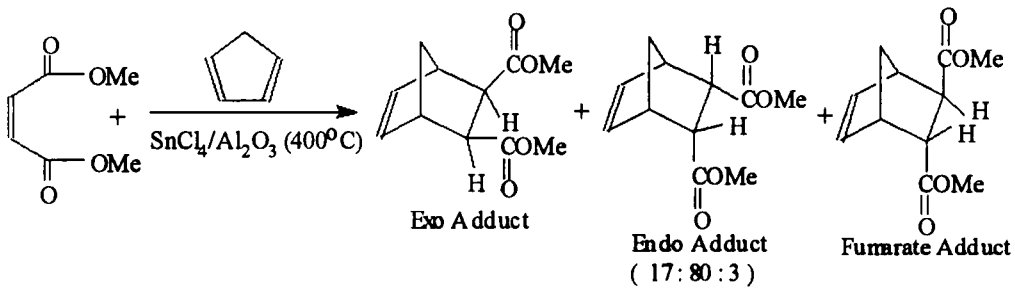
complexes. This reaction was also attempted on alumina modified by reaction with $SnCl_4$ and $TiCl_4$ to form the $SnCl_4/Al_2O_3$(400°C) and $TiCl_4/Al_2O_3$(400°C) complexes, respectively.

vi. Reaction of Dimethyl Maleate and Cyclopentadiene on the $SnCl_4/Al_2O_3$(400°C) Complex.

(a) Preparation of $SnCl_4/Al_2O_3$(400°C).

The $SnCl_4/Al_2O_3$(400°C) was prepared by slurring 10 ml of 1 M solution of $SnCl_4$ in dichloromethane and 10 grams of alumina that had been activated at 400°C under vacuum for 30 minutes at room temperature. After removing the solvent in vacuo, the $SnCl_4/Al_2O_3$(400°C) was stored under argon.

(b) DMM (6.0 mmol) was first added to the $SnCl_4/Al_2O_3$(400°C) complex. After stirring the mixture for 5 minutes, CP (6.0 mmol) was added in one portion and the resulting mixture was then stirred under argon at room temperature for 15 hours. After work up, the product mixture was shown by GC/MS analysis to be a 3:17:80 mixture of the fumarate, exo and endo DMM adducts, with a total yield of 54.5%. (eq 18).



(18)

The total yield of the cycloadducts on $SnCl_4/Al_2O_3$, 54.5%, was also lower that the total yield of cycloadducts obtained for the BBr_3/Al_2O_3(400°C) (89.0%) and BCl_3/Al_2O_3(200°C) complexes (70.5%). There was less fumarate adduct formed as well. If one assumes that the fumarate adduct only arises by prior isomerization of DMM to DMF, the rate of isomerization must be less on $SnCl_4/Al_2O_3$(400°C) than on BBr_3/Al_2O_3(400°C).

The decrease in the yield of the cycloadducts on the $SnCl_4/Al_2O_3$ complex compared to the BBr_3/Al_2O_3 complexes may be due to the Sn being less catalytically active than boron or to the overcrowding of the chemisorbed $SnCl_4$ because Sn (atomic radius = 1.405Å) is much larger in size than B (atomic radius = 0.83Å) (Figure III-6). This overcrowding of the surface of alumina would inhibit easy access of the dienophiles to the chemisorbed Sn, thus retarding the rate of the reaction.

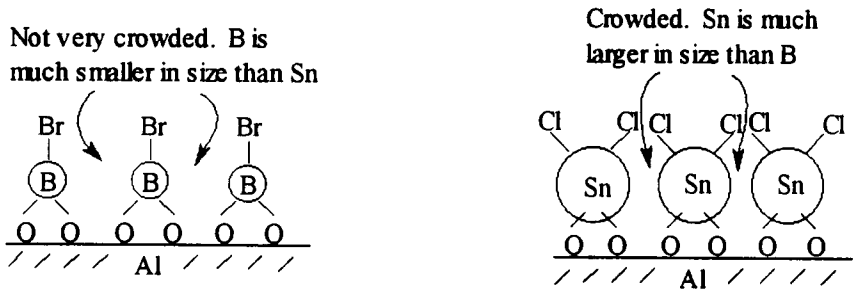


Figure III-6. The Overcrowding of the Chemisorbed $SnCl_4$ on Alumina is Not Found in BBr_3/Al_2O_3.

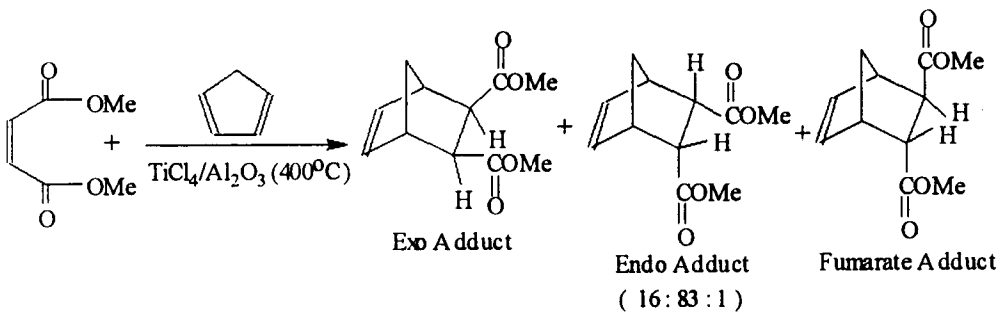
vii. Reaction of Dimethyl Maleate and Cyclopentadiene on the $TiCl_4/Al_2O_3$(400°C) Complex.

(a) Preparation of the $TiCl_4/Al_2O_3$(400°C) Complex

The $TiCl_4/Al_2O_3$(400°C) complex was prepared by slurring 10 ml of a 1M solution of titanium chloride in dichloromethane at room temperature for 30 minutes with 10

grams of alumina that had been activated at 400°C under vacuum for 4 hours. After removing the solvent in vacuo, the $TiCl_4/Al_2O_3$(400°C) complex was stored under argon.

(b) The reaction of DMM and CP was performed on $TiCl_4/Al_2O_3$ (400°C) as previously described for the reaction of DMM and CP on $SnCl_4/Al_2O_3$(400°C). Analysis of the product mixture by GC/MS showed the presence of the fumarate, exo and endo adducts in a ratio of 1:16:83, with a total yield of cycloadducts of 50.3% (eq 19).



(19)

The results show that very little fumarate adduct is generated on $TiCl_4/Al_2O_3$(400°C), especially when compared to the results on BBr_3/Al_2O_3(400°C). The rate of isomerization of DMM to DMF on $TiCl_4/Al_2O_3$(400°C) clearly occurs at a much slower rate than on BBr_3/Al_2O_3(400°C) or BCl_3/Al_2O_3(200°C) such that almost all of the DMM reacted with CP to form the endo and exo adducts before it could isomerize to DMF. The overall yield obtained on $TiCl_4/Al_2O_3$ (400°C), 50.3%, is also lower than the total yield of the cycloadducts on the 10 mmol BBr_3/10 g Al_2O_3 (400°C) and 10 mmol BCl_3/10 g Al_2O_3 (200°C). The decrease in the yield of the cycloadducts may again be attributed to the fact that Ti is less catalytically active or the overcrowding of $TiCl_4$ on the surface of the alumina since the size of a titanium atom (atomic radius = 1.448)[13] is

also larger than the size of a boron atom (atomic radius = 0.83Å).[13] An interesting experiment to try in the future would be to reduce the loadings of $SnCl_4$ and $TiCl_4$ on the alumina and see if this had the expected effects on the overall yield of adducts.

In conclusion, the rate of isomerization of DMM to DMF occurs faster on BBr_3/Al_2O_3(400°C) than on BCl_3/Al_2O_3(200°C), $SnCl_4/Al_2O_3$(400°C) and $TiCl_4/Al_2O_3$(400°C). The greater rate of isomerization on BBr_3/Al_2O_3 than BCl_3/Al_2O_3, and no isomerization on BF_3/Al_2O_3, is consistent with the known Lewis acid strengths of the boron trihalides and the boron trihalides/alumina complexes, where the order is: $BF_3 < BCl_3 < BBr_3$[11] and $BF_3/Al_2O_3 < BCl_3/Al_2O_3 < BF_3/Al_2O_3$. Therefore, the complex with a higher Lewis acid strength afforded the higher rate of isomerization of DMM to DMF. Moreover, the complex with the higher Lewis acid strength also gave a higher total yield of adducts.

The $SnCl_4/Al_2O_3$ (400°C) and $TiCl_4/Al_2O_3$ (400°C) complexes gave only small amounts of the fumarate adduct and a lower overall yield in the reaction of DMM with CP compared to the BBr_3/Al_2O_3 (400°C) complex. The $SnCl_4/Al_2O_3$ (400°C) and $TiCl_4/Al_2O_3$ (400°C) complexes are poorer catalysts than the BBr_3/Al_2O_3 (400°C) or the BCl_3/Al_2O_3 (200°C) complexes although steric effects due to overcrowding of the chemisorbed $SnCl_4$ and $TiCl_4$ may play a role in the reduced yields.

In the reaction between MA and ISP, the BBr_3/Al_2O_3(400°C) complex not only increased the total yield of the adducts from 52.3% to 60.2% compared to the reaction run neat, but also the 1,4-disubstituted to the 1,3-disubstituted ratio of adducts from 85:15 to 90:10.

Lewis acid/alumina complex catalysis of the Diels-Alder reaction is clearly significant for several of the complexes examined. The complexes may catalyze other reactions as well. Among them, the Friedel-Crafts alkylation or acylation reactions are promising candidates.

B. Competition Reaction of Cyclopentadiene with Two Dienophiles on Alumina and BBr_3/Al_2O_3 Complexes.

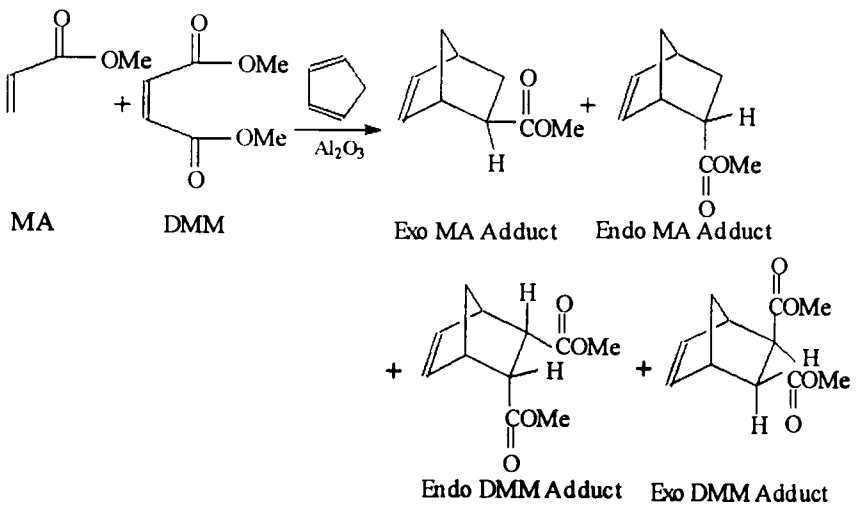
i. Competition Reaction of Cyclopentadiene with Methyl Acrylate, Dimethyl Maleate, and Dimethyl Fumarate Dienophiles on Alumina.

Competitive experiments where two dienophiles compete for CP on aluminas and BBr_3/Al_2O_3 complexes were performed to see the effect that these catalysts had on the relative reactivity of the dienophiles. Competition experiments were run in place of the direct measurement of the rate constants because these experiments are so much easier to run, especially in a heterogeneous reaction, and the results are almost as useful. Problems can occur, however, in the competition experiments; these will be discussed later.

a. Competition Reactions between Methyl Acrylate (MA) and Dimethyl Maleate (DMM) for Cyclopentadiene on Unactivated and Activated Alumina.

The dienophiles, MA (4.0 mmol) and DMM (4.0 mmol), were first mixed in a small vial, and then added to alumina (12.5 g) that had been activated at 400°C under

vacuum for 4 hours [Al_2O_3/(400°C)]. After stirring the mixture for 20 minutes at room temperature, cyclopentadiene (5 mmol) was added via a syringe and the reaction mixture stirred under argon for 1 hour. Upon completion of the reaction, the product mixture was worked up and analyzed by the GC/MS. The same competitions were repeated on Al_2O_3(700°C), Al_2O_3(300°C), Al_2O_3(200°C), Al_2O_3(100°C), and Al_2O_3(unactivated). There was no distinct color change on the aluminas when cyclopentadiene was added to the mixture of dienophiles and alumina. The yields of the Diels-Alder adducts and the ratio of the rate constants for the reactions between MA and DMM with CP on the unactivated alumina are summarized in equation 20 and Table III-4, page 200.



(20)

The method used to determine the relative rates is shown below. Consider the reaction of two dienophiles, DMM and MA, with CP on a surface of a solid, which produces products, P_x and P_y, respectively. It is assumed that the surface is homogenous or, if not, that any structural features on the surface of the solid are randomly distributed. Thus, the surface reactions are assumed to behave as solution reaction do.

Let the reaction of CP + DMM be of the form

$$CP + DMM \xrightarrow{k_x} P_x, \quad \text{where } DMM_o = DMM + P_x \qquad (i)$$

and the reaction of CP + MA be of the form

$$CP + MA \xrightarrow{k_y} P_y, \quad \text{where } MA_o = MA + P_y \qquad (ii)$$

The differential second order rate equation for (i) and (ii) would then be

$$\frac{dP_x}{dt} = k_x [CP] [DMM], \text{ and}$$

$$\frac{dP_y}{dt} = k_y [CP] [DMM], \text{ respectively,}$$

where [ ] = concentration of the sustrate in moles/m^2

Therefore,

$$\frac{dP_x}{dP_y} = \frac{dP_x}{dt} \div \frac{dt}{dP_y}$$

$$= \frac{k_x [DMM]}{k_y [MA]}$$

Since $DMM_o = DMM + P_x$ and $MA_o = MA + P_y$,

therefore,

$$\frac{dP_x}{dP_y} = \frac{k_x ([DMM]_o - [P_x])}{k_y ([MA]_o - [P_y])}$$

Thus,

$$\frac{dP_x}{([DMM]_o - [P_x])} = \frac{k_x dP_y}{k_y ([MA]_o - [P_y])}$$

On intergration gives

$$- \ln ([DMM]_o - [P_x]) \Big|_0^{P_x} = - \frac{k_x}{k_y} \ln ([MA]_o - [P_y]) \Big|_0^{P_y}$$

Insertion of the limits and rearrangements give, finally

$$\ln \left(\frac{[DMM]_o - [P_x]}{[DMM]_o} \right) = \frac{k_x}{k_y} \ln \left(\frac{[MA]_o - [P_y]}{[MA]_o} \right)$$

The ratio of the rate constants for the competitive reactions, k_x/k_y, can, therefore, be obtained if known amounts of the two dienophiles are used in the reaction and the amounts of the two products after a given reaction time are known.

To see how these results compared to those obtained in solution, a study was carried out by reacting DMM (4.0 mmol) and MA (4.0 mmol) with CP (5.0 mmol) in 3 ml diethyl ether. The reaction mixture was stirred at room temperature under argon for 4 hour. Upon completion of the reaction, the product mixture was quenched with three portions of methanol (20 ml) and then extracted twice with 30 ml of diethyl ether. After removal of the solvent, the product mixture was analyzed by GC/MS. The results of this reaction are also presented in Table III-4.

Table III-4. Competition Reactions of Cyclopentadiene with Methyl Acrylate and Dimethyl Maleate on Aluminas and in Diethyl Ether.[a]

Alumina	k_{DMM}/k_{MA}[b]	DMM Adduct				% MA Adduct		
		Fum[c]	Exo[c]	Endo[c]	Total[c]	Exo[d]	Endo[d]	Total[d]
Al_2O_3(Unact'd)	3.86	-	10.60	38.48	49.08	0.58	15.48	16.06
Al_2O_3(100°C)	0.716	-	2.76	15.61	18.37	7.40	17.28	24.68
Al_2O_3(200°C)	0.935	-	4.96	27.99	32.93	6.32	28.45	34.77
Al_2O_3(300°C)	0.469	-	7.14	28.48	36.62	1.77	60.4	62.17
Al_2O_3(400°C)	1.74	-	2.12	20.69	22.81	0.45	15.45	15.90
Al_2O_3(700°C)	-	14.16	1.91	15.85	31.92	6.64	55.62	62.26
Diethyl Ether	0.609	-	2.43	15.85	17.76	4.40	8.54	12.94

[a] The reactions were run for 4 hours.

[b] k_{DMM} = rate constant of the reaction of DMM for cyclopentadiene. k_{MA} = rate constant of the reaction of MA for cyclopentadiene.

[c] Fum = % Fumurate DMM adduct; Exo = % Exo DMM adduct; Endo = % Endo DMM adduct; Total = (% Fum + %Exo + %Endo) DMM adducts

[d] Exo = % Exo MA adduct; Endo = %Endo MA adduct; Total = (%Exo + %Endo) MA adducts

It is well known that DMM is approximately ½ as reactive as MA toward CP in solution.[12] The competitive experiments in diethyl ether yield a similar result. The k_{DMM}/k_{MA} values obtained on the Al_2O_3(100°C) and Al_2O_3(300°C) complexes are also fairly consistent with the literature solution value. The k_{DMM}/k_{MA} values obtained on the Al_2O_3 (unactivated), Al_2O_3(200°C) and Al_2O_3(400°C), however, are much larger than the k_{DMM}/k_{MA} values obtained in solution. A plot of the k_{DMM}/k_{MA} versus the activation temperature of the alumina is shown in Figure III-7. The relative reactivity of these dienophiles toward CP changes significantly as the activation temperature is increased gradually. Clearly the temperature at which the alumina is activated plays a significant role in the rates of the Diels-Alder reactions although the exact reason for the behavior

shown in Figure III-7 is not known. Additional work will be necessary to rationalize the trend.

The one thing in particular to note in Table III- 4 is the fact that the fumarate adduct is generated in the DMM-CP reaction on Al_2O_3(700°C). Similar behavior has been reported previously.

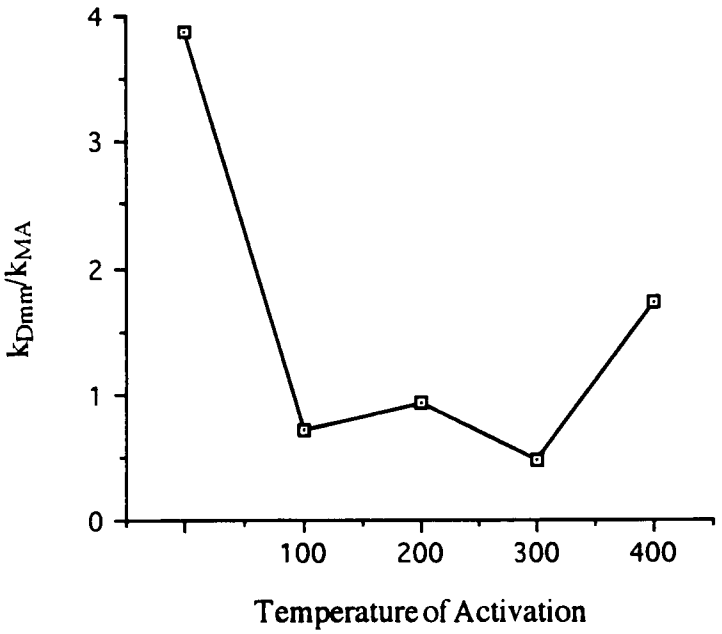


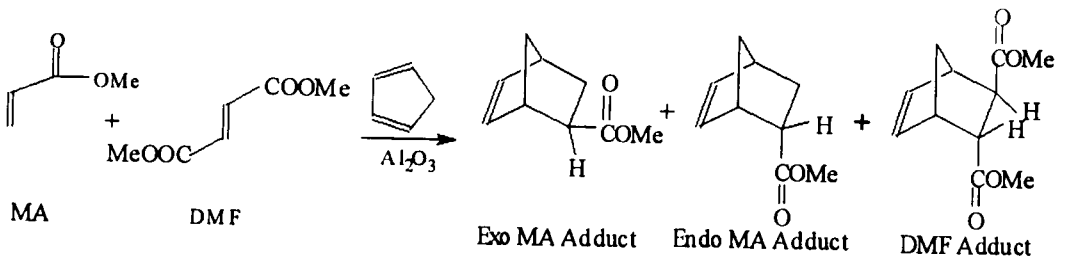
Figure III-7. Plot of k_{DMM}/k_{MA} versus the Activation Temperature of Alumina.

(b) Competition Reaction between Dimethyl Fumarate and Methyl Acrylate for Cyclopentadiene on Alumina.

A solution of DMF (4.0 mmol) and MA (4.0 mmol) in 3 ml of diethyl ether was added via syringe to alumina (12.5 g), which had been activated at 400°C for 4 hours under vacuum. The diethyl ether was removed in vacuo at 40°C. The mixture was then

stirred for 20 minutes before CP (5.0 mmol) was added via syringe and the reaction mixture stirred for 4 hour under argon. The product mixture was then worked up and analyzed by GC/MS. The same procedure was subsequently carried out on the Al_2O_3/(200°C) and Al_2O_3/(unactivated). The yields of the Diels-Alder adducts for the reactions between DMF and MA toward CP on the unactivated and the various aluminas are shown in Table III-5.

A study was also carried out by reacting DMF (4.0 mmol) and MA (4.0 mmol) with CP (5.0 mmol) in 3 ml of diethyl ether at room temperature for 4 hours as described for the reaction between DMM and MA with CP in 3 ml of diethyl ether. The results obtained by analysis of the product mixture by GC/MS as shown in Table III-5



MA DMF Exo MA Adduct Endo MA Adduct DMF Adduct (21)

Table III-5. Competition Reactions of Cyclopentadiene with Dimethyl Fumarate and Methyl Acrylate on Aluminas and in Diethyl Ether.[a]

Al_2O_3 Complex	k_{DMF}/k_{MA}[b]	% DMF Adduct	% MA Adduct		
			Exod[c]	Endo[c]	Total[c]
Al_2O_3(Unact'd)	2.38	20.84	1.77	7.59	9.36
Al_2O_3(200°C)	0.606	30.46	1.15	56.29	57.44
Al_2O_3(400°C)	1.53	5.78	0.04	3.78	3.82
Diethyl Ether	1.66	77.77	14.90	44.70	59.60

[a]All the reactions were run for 4 hours

[b]k_{DMF} = rate constant of the reaction of DMF for cyclopentadiene. k_{MA} = rate constant of the reaction of MA for cyclopentadiene.

[c]Exo = % Exo MA adduct; Endo = %Endo MA adduct;
Total = (%Exo + %Endo) MA adducts

Surprisingly, k_{DMF}/k_{MA} was 1.66 when the competition reaction was carried out in diethyl ether. This was not expected because the relative rate of DMF is ~ 62 times greater than that of MA in solution based on the absolute rate constants for these reactions in solution.[12] This is not really surprising, however, because competition experiments do not work well when the competing reactions occur at vastly different rates.

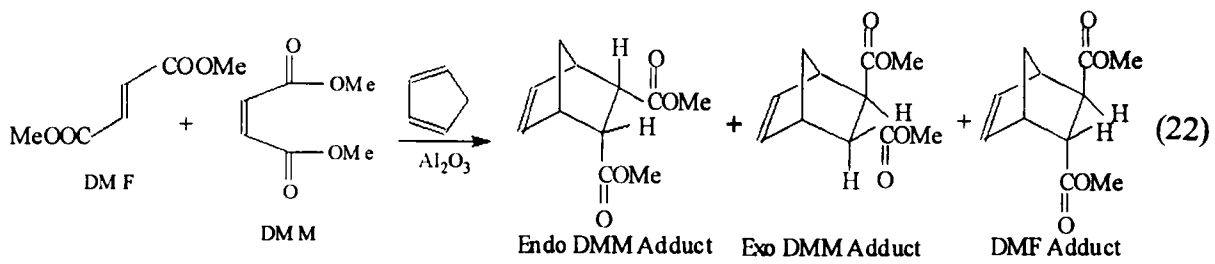
There is clearly something wrong with the experiment in ether because the total yield of all the products is 137.37%. As the reaction was run with 4.0 mmol of each dienophile and 5.0 mmol of CP, the maximum total yield is 120%. Furthermore, when one dienophile is much more reactive than the other, it is possible for the more reactive dienophile to be completely consumed before the other starts to react. Thus, if the competition is run for too long a time, a false relative reactivity will be obtained. Anytime one gets a large total yield from one dienophile, as it is for DMF (77.77%), the

results should be considered suspicious for this reason. As neither of this problem occurs on the solids, these results are probably correct. In hindsight, it would have been better to have run the reaction with a deficiency of CP and the problems just described would have been avoided.

On the solids, except for the value of $k_{DMF}/k_{MA} = 0.606$, which was obtained on Al_2O_3(200°C), the k_{DMF}/k_{MA} values for the Al_2O_3(unactivated) and the Al_2O_3(400°C) were slightly greater than 1. Because of the problem encountered in the solution reaction, the relative reactivities on the solids are somewhat suspect.

(c) Competition Reaction between Dimethyl Maleate and Dimethyl Fumarate for Cyclopentadiene on Alumina.

A solution of DMF (4.0 mmol) and DMM (4.0 mmol) in 3 ml of diethyl ether was added via syringe to alumina (12.5 g), which had been activated at 400°C for 4 hours under vacuum. The diethyl ether was removed in vacuo at 40°C. The reaction mixture was then stirred for 20 minutes before CP (5.0 mmol) was added via syringe and the reaction mixture stirred for 1 hour under argon. The reaction was then worked up and analyzed by GC/MS. The same procedure was subsequently carried out on the Al_2O_3(200°C) and Al_2O_3 (unactivated). The reactions gave the expected products (eq 22). The yields of the Diels-Alder adducts for the reactions between DMF and DMM toward CP on the unactivated and the various aluminas are shown in Table III-6.



(22)

A study was also carried out by reacting DMF (4 mmol) and DMM (4 mmol) with CP (5 mmol) in 3 ml of diethyl ether. The reaction mixture was stirred at room temperature under argon for 4 hours. After stirring for 4 hours, the reaction was worked up and analyzed by GC/MS. The result of this reaction is also tabulated in Table III-6.

Table III-6. Competition Reactions of Cyclopentadiene with Dimethyl Maleate and Dimethyl Fumarate on Aluminas and Diethyl Ether.[a]

Al_2O_3 Complex	k_{DMM}/k_{DMF}[b]	% DMM Adduct			% DMF Adduct
		Exo[c]	Endo[c]	Total[c]	
Al_2O_3(Unact'd)	0.969	14.54	33.92	48.45	49.50
Al_2O_3(200°C)	0.956	14.97	33.33	48.30	49.82
Al_2O_3(400°C)	0.946	13.50	34.71	48.21	50.11
Diethyl Ether	0	0	0	0	9.79

[a] All the reactions were run for 4 hours.

[b] k_{DMF} = rate constant of the reaction of DMF for cyclopentadiene. k_{DMM} = rate constant of the reaction of DMF for cyclopentadiene.

[c] Exo = % Exo DMM adduct; Endo = % Endo DMM adduct; Total = (%Exo + %Endo) DMM adducts

The k_{DMM}/k_{DMF} was 0 when the competition reaction was carried out in diethyl ether. This is expected because k_{DMF} is more reactive in solution than k_{DMM} by a factor of about one hundred.[12] The data in Table III-6 revealed that all k_{DMM}/k_{DMF} values for

the competition reactions that were run on the aluminas are approximately 1. This is interesting because DMF is as just noted, about 100 times more reactive than DMF toward CP in solution.[12] The difference observed on the solids must be due to the effect of the surface of alumina on the reagents used in these reactions. When DMM and DMF are adsorbed on the alumina, the carbonyl oxygen lone pairs of the DMM and DMF complex with the partially exposed Al^{+3}s which catalyze their reactions toward CP. The acid-catalyzed reactions on the surface must occur at comparable rates.

The competitive reactions were run with three pairs of dienophiles, DMM-MA, DMF-MA and DMM-DMF and the respective rate constant ratios, k_{DMM}/k_{MA}, k_{DMF}/k_{MA} and k_{DMM}/k_{DMF}, were found experimentally. What is interesting about the rate constant ratios obtained from these competition reactions is the fact that if two rate constant ratios, e.g., k_{DMM}/k_{MA} and k_{DMF}/k_{MA} are known, it is possible to calculate the third one, k_{DMM}/k_{DMF}. The values computed in the above case for the unactivated alumina, Al_2O_3/200°C and Al_2O_3/400°C are 1.62, 1.54 and 1.14, respectively. The prediction is thus fairly close, but not identical to, the experimental values which are 0.969, 0.956 and 0.946, respectively. These predicted values are calculated as shown below.

For the Al_2O_3(unactivated):

$k_{DMM}/k_{MA} = 3.63$ and $k_{DMF}/k_{MA} = 2.38$.

$\therefore$ The predicted value for $k_{DMM}/k_{DMF} = 3.86 \div 2.38 = 1.62$.

For the Al_2O_3(200°C):

k_{DMM}/k_{MA} = 0.935 and k_{DMF}/k_{MA} = 0.606.

∴ The predicted value for k_{DMM}/k_{DMF} = 0.935 ÷ 0.606 = 1.54.

For the Al_2O_3(400°C):

k_{DMM}/k_{MA} = 1.74 and k_{DMF}/k_{MA} = 1.53.

∴ The predicted value for k_{DMM}/k_{DMF} = 1.74 ÷ 1.53 = 1.14.

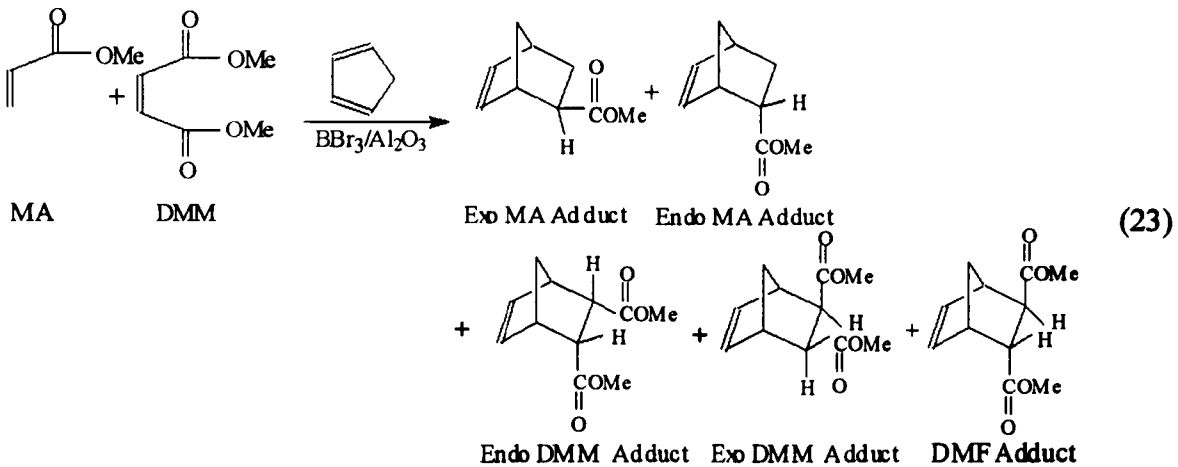
ii. Competition Reaction of Cyclopentadiene with Methyl Acrylate, Dimethyl Maleate, and Dimethyl Fumarate on BBr_3/Al_2O_3 Complexes.

(a) Competition Reactions between MA and DMM for CP on the Various BBr_3/Al_2O_3 Complexes.

In these experiments, the dienophiles, MA (4.0 mmol) and DMM (4.0 mmol), were mixed together and then added to 12.5 grams of the BBr_3/Al_2O_3 complex (10 mmol BBr_3/10 g Al_2O_3(400°C) in a round bottom flask via syringe. After stirring for 20 minutes, CP (5.0 mmol) was added via syringe. The reaction mixture was stirred under argon for 4 hour at room temperature and then quenched with three portions of methanol. After extraction with diethyl ether, the combined organic phase was removed in vacuo, and the product mixture was analyzed by GC/MS. The same procedure was also carried out on the BBr_3/Al_2O_3(300°C), BBr_3/Al_2O_3(200°C), BBr_3/Al_2O_3(100°C),

BBr_3/Al_2O_3(unactivated). When CP was added onto the mixture of the BBr_3/Al_2O_3 complex and the dienophiles, the color of the the mixture turned from white to lavender pink or dark lavender. The color gradually changed to a dark reddish purple over the course of the reaction. This gradual change took about 15 minutes. The presence of the MA-CP and DMM-CP adducts was confirmed by comparing the GC retention times and mass spectra of the products with the retention times and mass spectra of known compounds. The yields of the Diels-Alder adducts and the ratio of the rate constants for the reaction of CP and the dienophiles are summarized in Table III-7 (eq 23).

The original intension for performing the competition reactions between two dienophiles (DMM-MA) with CP on BBr_3/Al_2O_3 complexes was, of course, to determine k_{DMM}/k_{MA}. However, at that time it was not known that DMM isomerized to DMF when in contact with the BBr_3/Al_2O_3 complexes. Therefore, the k_{DMM}/k_{MA} values shown in Table III-7 are not real because of the competing isomerization of DMM to DMF. As shown later, similar results were obtained with the DMM-DMF pair.



(23)

Table III-7. Competition Reactions of Cyclopentadiene with Methyl Acrylate and Dimethyl Maleate on BBr_3/Al_2O_3 Complexes.[a]

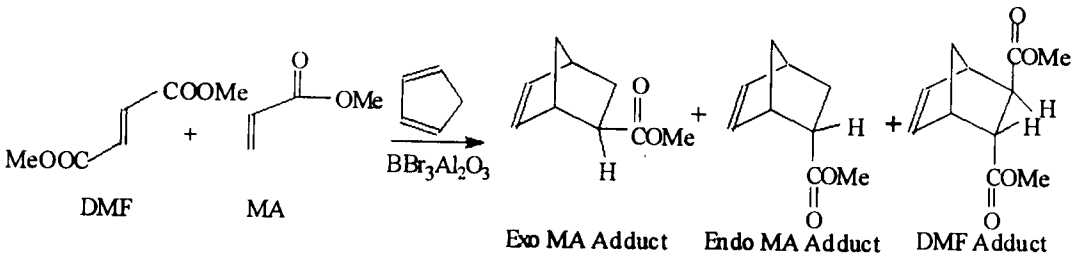
BBr_3/Al_2O_3 Complex[b]	k_{DMM}/k_{MA}[c]	% DMM Adduct				% MA Adduct		
		Fum[d]	Exo[d]	Endo[d]	Total[d]	Exo[e]	Endo[e]	Total[e]
BBr_3/Al_2O_3(unact'd)	4.72	45.81	1.03	2.88	49.72	1.81	11.94	13.55
BBr_3/Al_2O_3(100°C)	4.32	59.20	0.64	3.68	63.52	2.43	18.38	20.31
BBr_3/Al_2O_3(200°C)	0.90	52.22	0	0	52.22	6.24	49.90	56.14
BBr_3/Al_2O_3(300°C)	3.61	65.83	0	0	65.83	3.67	22.03	25.70
BBr_3/Al_2O_3(400°C)	1.98	14.05	0	0	14.05	0.94	6.41	7.35

[a] All the reactions were run for 4 hours.
[b] 10 mmol BBr_3/10 g Al_2O_3 was used in each case.
[c] k_{DMM} = Rate constant for the reaction of DMM for CP; k_{MA} = Rate constant for the reaction of MA for CP
[d] Fum = % Fumurate DMM adduct; Exo = % Exo DMM adduct; Endo = % Endo DMM adduct; Total = (% Fum + %Exo + %Endo) DMM adducts. Total = (%Exo + %Endo) MA adducts
[e] Exo = % Exo MA adduct; Endo = %Endo MA adduct;

(b) Competition Reaction between Dimethyl Fumarate and Methyl Acrylate for Cyclopentadiene on the Various BBr_3/Al_2O_3 Complexes.

A solution of DMF (4.0 mmol) and MA (4.0 mmol) in 3 ml of diethyl ether was added to 12.5 grams of the BBr_3/Al_2O_3 complex [10 mmol BBr_3/10 g Al_2O_3(400°C)] via syringe. The diethyl ether was removed in vacuo at 40°C. The mixture was then stirred for 20 minutes before CP (5.0 mmol) was added via syringe. After stirring the reaction mixture under argon for 1 hour, the product mixture was worked up and analyzed by GC/MS. The competition reactions were repeated on the BBr_3/Al_2O_3(200°C) and BBr_3/Al_2O_3(unactivated) complexes. As was observed in the competition reactions of DMM and MA with CP, a color change was also observed here. The color turned from

white to lavender pink or dark lavender upon addition of CP. Within another 15 minutes, the dark lavender mixture gradually changed to a dark reddish purple. The yields of the Diels-Alder adducts of the reaction of DMF and MA with CP on the various BBr_3/Al_2O_3 complexes are listed in Table III-8 (eq 24). These results do have meaning because DMF does not isomerize to DMM under the reaction conditions.



(24)

Table III-8. Competition Reactions of Cyclopentadiene with Dimethyl Fumarate and Methyl Acrylate on BBr_3/Al_2O_3 Complexes.[a]

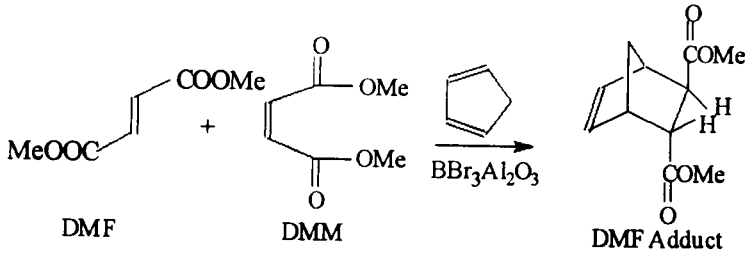
BBr_3/Al_2O_3 Complex[b]	% DMF adduct	% MA adduct		
		Exo[c]	Endo[c]	Total[c]
BBr_3/Al_2O_3(Unact'd)	22.02	0	0	0
BBr_3/Al_2O_3(200°C)	58.80	0	0	0
BBr_3/Al_2O_3(400°C)	70.50	0	0	0

[a] All the reactions were run for 4 hours.
[b] 10 mmol BBr_3/10 g Al_2O_3 was used in all cases.
[c]Exo = % Exo MA adduct; Endo = % Endo MA adduct; Total = (% Exo + %Endo) MA adduct.

For the three cases shown in Table III-8, only the DMF adduct was formed; no MA adducts were observed. These results are similar to what is expected in solution with no catalyst.

c) Competition Reaction between Dimethyl Maleate and Dimethyl Fumarate for Cyclopentadiene on the Various BBr_3/Al_2O_3 Complexes.

For the competition reactions between DMM (4.0 mmol) and DMF (4.0 mmol), the solid DMF was first dissolved 3 ml of diethyl ether in a small vial. After adding the DMM to the solution, the mixture was added to 12.5 grams of the BBr_3/Al_2O_3 complex [10 mmol BBr_3/10 g Al_2O_3] in a round bottom flask via syringe. The diethyl ether was removed in vacuo at 40°C. The mixture was then stirred for 20 minutes. Cyclopentadiene (5.0 mmol) was then added to the solid and the resulting mixture stirred under argon for 4 hour. The color of the solid turned from white to lavender pink or dark lavender, as was the case for the the reaction of MA and DMM cyclopentadiene described above. The product mixture was worked up and analyzed by the GC/MS. The same competition reaction procedure was used to run the competion reactions on BBr_3/Al_2O_3(200°C) and BBr_3/Al_2O_3(unactivated). The yields of the Diels-Alder adducts of the reactions of the DMM and DMF dienophiles with cyclopentadiene on the various BBr_3/Al_2O_3 complexes are presented in Table III-9 (eq 25). Because DMM isomerizes to DMF under the reaction condition, it is not possible to calculate meaningful k_{DMM}/k_{DMF} values.



(25)

Table III-9. Competition Reactions of CP with DMM and DMF on the Various BBr_3/Al_2O_3 Complexes.[a]

BBr_3/Al_2O_3 Complex[b]	% DMM adduct			% DMF adduct
	Exo[c]	Endo[c]	Total[c]	Total Fum
BBr_3/Al_2O_3(Unact'd)	0	0	0	32.82
BBr_3/Al_2O_3(200°C)	0	0	0	24.02
BBr_3/Al_2O_3(400°C)	0	0	0	43.24

[a] The reactions were run for 4 hours.
[b] 10 mmol BBr_3/10 g Al_2O_3 was ised in all cases.
[c] Exo = % Exo DMM adduct; Endo = % Endo DMM adduct; Total = (% Exo + %Endo) DMM adduct.

The results of the competition reactions between the dienophiles and cyclopentadiene on 2 mmol BBr_3/g Al_2O_3 and the 3 mmol BBr_3/g Al_2O_3 complexes are described in the following sections.

(d) Reaction between Dimethyl Maleate (DMM) and Methyl Acrylate (MA) for Cyclopentadiene on the 1 mmol , 2 mmol and 3 mmol BBr_3/g Al_2O_3(400°C) Complexes.

To a small vial containing a mixture of the dienophile (4 mmol DMM and 4 mmol CP) was added to the 12.5 g of 2 mmol BBr_3/g Al_2O_3(400°C) complex. After stirring the mixture for 20 minutes, cyclopentadiene (5 mmol) was added via a syringe after which the mixture gradually turned from dark pink to dark red over a period of 15 minutes. The reaction mixture was stirred under argon for 4 hour. Upon completion of the reaction, the product mixture was quenched with methanol, worked up and analyzed by GC/MS.

The reaction was repeated identically on 3 mmol BBr_3/g Al_2O_3(400°C). The results of the reaction are summarized in Table III-10.

Table III-10. Competition Reactions of Cyclopentadiene with Dimethyl Maleate and Methyl Acrylate on the 2 mmol and 3 mmol BBr_3/g Al_2O_3 (400°C) Complexes.[a]

mmol BBr_3/g Al_2O_3	% DMM adduct				% MA adduct		
	Fum	Exo	Endo	Total	Exo	Endo	Total
1 mmol/g[b]	14.05	0	0	14.05	0.94	6.41	7.35
2 mmol/g	5.44	0	5.23	10.97	1.67	9.49	11.16
3 mmol/g	7.08	0	7.45	14.53	2.76	12.60	15.36

[a] All reactions were run for 4 hours.

[b] This data was taken from Table III-7, page 209.

Isomerization of DMM to DMF occurred on all BBr_3/Al_2O_3s, but it occurred to a lesser extent on the 2 mmol BBr_3/g Al_2O_3 and 3 mmol BBr_3/g Al_2O_3 than on the 1 mmol BBr_3/g Al_2O_3. It appears that all the DMM had isomerized to DMF on 1 mol BBr_3/g Al_2O_3 before reacting with CP to form the DMF-CP adduct exclusively, while only ~ 50 % of DMM had isomerized to DMF on the 2 mmol BBr_3/g Al_2O_3 and 3 mmol BBr_3/g Al_2O_3, respectively. The total yield of the DMM adducts is about the same for the 1 mmol BBr_3/g Al_2O_3 and the 3 mmol BBr_3/g Al_2O_3, but is slightly less for the 2 mmol BBr_3/g Al_2O_3.

The effect of the loading of the BBr_3 on alumina on the endo/exo ratio for the MA-CP adduct is also interesting. The endo/exo value for the 1 mmol BBr_3/g Al_2O_3 is 6.82, which decreases to 5.68 and 4.57 for the 2 mmol BBr_3/g Al_2O_3 and 3 mmol

BBr_3/g Al_2O_3, respectively. The reaction of MA with CP in this case showed more selectivity with the lower loadings of BBr_3. The total yield of MA adducts, however, is quite different from the trend of the total yield of DMM adducts. The yield increased from 7.35% for the 1 mmol BBr_3/g Al_2O_3 to 11.16% and 15.36%, for the 2 mmol BBr_3/g Al_2O_3 and 3 mmol BBr_3/g Al_2O_3, respectively.

EXPERIMENTAL SECTION

A. Materials

i. Solvents

Acetone, Mallinkrodt, ACS grade*

Methanol, Aldrich Chemical Co.*

Anhydrous Ethyl Ether, Mallinkrodt, ACS grade*

Hexanes, Mallinkrodt, ACS grade*

* The solvent was used a purchased.

ii. Gases

Argon, Ar MG Industries, prepurified Ar was used without further pruification.

(iii) Reagents

Methyl acrylate, Aldrich Chemical Co.**

Dimethyl maleate, Aldrich Chemical Co.**

Dimethyl fumarate, Aldrich Chemical Co.**

Hexadecane, Aldrich Chemical Co.**

Boron tribromide-etherate, 1.0 M solution, Aldrich Chemical Co.**

Dicyclopentadiene, Aldrich Chemical Co.**

Maleic Anhydride, Aldrich Chemical Co.**

Boron trichloride, 1.0 M solution in dichloromethane, Aldrich Chemical Co.**

Boron trifluoride etherate, Aldrich Chemical Co.**

Isoprene, Aldrich Chemical Co.**

Titanium (IV) chloride, 1.0 M solution in dichloromethane, Aldrich Chemical Co.**

Tin (IV) chloride, 1.0 M solution in dichloromethane, Aldrich Chemical Co.**

Alumina, Brockman Activity Grade 1, Fisher Scientific, alumina was used as received.

Activated alumina, Brockmann acitvity grade 1, Fisher Scientific, activated alumina was prepared using the method and appartus described by Pagni *et al.*[20] as described in the Experimental Section in part II, page .

** The reagent was used as received.

B. Experimental Methods

i. Analytical Methods

Preparative gas chromatography was performed using a Varian 3300 gas chromatograph equipped with 6´ x 1/4" 20% SE-30 on chromasorb W column. Gas chromatography was also performed on a Hewlett-Packard 5890A GC instrument equipped with a 30 m x 1/8" column packed with 30% SE-30 by weight on Chromosorb W as the solid support. Gas chromatograph/Mass spectrometry (GC/MS) was performed using a Hewlettt-Packard 5970 Gas chromatograph/Mass spectrometer detector.

ii. Apparatus and Manipulation of Reagents

Due to the moisture sensitivity of the BX_3, $SnCl_4$ and $TiCl_4$ reagents, all manipulations were performed under dry argon atmosphere in a glove bag. All glassware, syringes and needles were oven-dried at 100°C for 6 hours, assembled hot, and cooled under a stream of argon before use. The reactions were performed under a slight positive pressure of argon using a pressure-regulated argon source with a mercury bubbler. All the reactions involving the boron trihalides $SnCl_4$, $TiCl_4$ and activated alumina were run under an argon atomsphere.

C. Experimental Procedures

i. Addition of Boron Tribromide to Alumina. Preparation of BBr_3/Al_2O_3 (400°C) Complex. General Procedure A.

A known amount of Brockmann alumina that had been activated at 400°C for 4 hours under vacuum (10 g) was placed in a 250 mL round bottom flask under an argon atmosphere. Hexanes (50 ml) were added by double ended 18 guage needle and the reaction flask was cooled to 0°C. The boron tribromide (1 M in hexanes) was then added slowly by a double ended 18 guage needle so that 1 mmol boron tribromide (1 molar in hexanes) was added per 1 gram of alumina. Hydrogen bromide gas is released during this reaction. The reaction mixture was allowed to stir for 30 minutes and excess solvent was removed in vacuo using dry ice/acetone traps to capture the hexanes and a

KOH or NaOH trap to capture acid. After evaporation of the hexanes, the BBr_3/Al_2O_3 (400°C) was once again stored in an air tight container under an argon atmosphere.

i (a) Preparation of BBr_3/Al_2O_3(300°C), BBr_3/Al_2O_3(200°C), BBr_3/Al_2O_3(100°C), and BBr_3/Al_2O_3 (unactivated) Complexes.

BBr_3/Al_2O_3(300°C), BBr_3/Al_2O_3(200°C), BBr_3/Al_2O_3(100°C), and BBr_3/Al_2O_3(unactivated) complexes were prepared according to the General Procedure A described for the preparation of the BBr_3/Al_2O_3(400°C) complex, page 217.

i (b) Preparation of BCl_3/Al_2O_3(200°C).

BCl_3/Al_2O_3(200°C) complex was prepared according to the General Procedure A described for the preparation of the BBr_3/Al_2O_3(400°C) complex, page 217. 1 M BCl_3 in hexanes was used in place of 1 M BBr_3 in hexanes.

i (c) Preparation of BF_3/Al_2O_3(400°C).

BF_3/Al_2O_3(400°C) complex was prepared according to the General Procedure A described for the preparation of the BBr_3/Al_2O_3(400°C) complex, page 217. 1 M BF_3-etherate was used in place of 1 M BBr_3 in hexanes.

i (d) Preparation of $SnCl_4/Al_2O_3$(400°C) Complex.

The $SnCl_4/Al_2O_3$(400°C) complex was prepared according to the General Procedure A described for the preparation of the BBr_3/Al_2O_3(400°C) complex, page 217. 1 M $SnCl_4$ in dichloromethane was used in place of 1 M BBr_3 in hexanes.

i (e) Preparation of $TiCl_4/Al_2O_3$(400°C) Complex.

The $TiCl_4/Al_2O_3$(400°C) complex was prepared according to the General Procedure A described for the preparation of the BBr_3/Al_2O_3(400°C) complex, page 217. 1 M $TiCl_4$ in dichloromethane was used in place of 1 M BBr_3 in hexanes.

ii. Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BBr_3/Al_2O_3 (400°C) Complex Performed under Argon. General Procedure B.

BBr_3/Al_2O_3 (400°C) complex (10.0 grams) was added to a 250 ml round bottom flask with a side arm. Dimethyl maleate (6 mmols) was then added to the alumina via a syringe and the reaction mixture was stirred for 10 minutes under argon at room temperature. At this moment, the cyclopentadiene (6 mmols) was added via syringe and the reaction mixture was stirred under argon for another 4 hours at room temperature. (Note: the duration of the reaction can be cut significantly to 10 to 20 minutes for reactions on this complex and BBr_3/Al_2O_3 (400°C) because the starting materials react almost instantaneously.) After the reaction period, the mixture was quenched with 50 ml of methanol and stirred for 1 hour. The product mixture was then worked up and analyzed according to the general procedure D described for the competition reaction

between methyl acrylate and dimethyl maleate with cyclopentadiene on the BBr_3/Al_2O_3 (400°C) complex, page 227. This reaction resulted in a 90:4:6 ratio of fumarate, exo, and endo DMM adducts, with a 89.0% overall yield of the cycloadducts. GC retention times (min): 29.138, 29.168 and 30.398 for the fumarate, exo and endo adduct. Coinjection with known materials confirmed the identity of the products.

ii. (a) Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BBr_3/Al_2O_3(400°C) Complex in Air.

The reaction procedure for the reaction between DMM and CP on the BBr_3/Al_2O_3 (400°C) complex, was used here (page 219). The amounts of reagents, reaction conditions and work up were identical to that described in the General Procedure B except this reaction was run in air. The ratio of the fumarate, exo, and endo DMM adducts was 90:0:1 with an overall yield of 88%. GC retention times (min) were 29.142, 29.223 and 30.534 for the fumarate, exo and endo adducts.

ii. (b) Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BBr_3/Al_2O_3(unactivated) Complex Under Argon.

The Diels-Alder reaction of DMM and CP was performed under argon in the presence of BBr_3/Al_2O_3(unactived) complex. The reaction procedure, the amounts of reagents and BBr_3/Al_2O_3(unactivated) complex and the method to analyze the product mixture were identical to that described in the General Procedure B, for the reaction between DMM and CP in the presence of BBr_3/Al_2O_3(400°C) complex under argon, page

219. The overall yield of adducts was 88.5%, formed in a ratio of fumarate:exo:endo DMM adducts of 95:2:3. GC retention time (min) were 29.101, 29.198 and 30.246 for the fumarate, exo and endo adducts.

ii. (c) Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BBr_3/Al_2O_3(400°C) Complex for 20 Minutes Under Argon.

The Diels-Alder reaction of DMM and CP was performed under argon in the presence of BBr_3/Al_2O_3(400°C) complex. The reaction procedure, the amounts of reagents and BBr_3/Al_2O_3(400°C) complex, and the method used to analyzse the product mixture were identical to that described in the General Procedure B, page 219, except the reaction time was reduced to 20 minutes. The fumarate, exo and endo DMM adducts were formed in a 90:0:1 ratio, with a overall yield of 85.0%. GC retention times (min) were 29.137, 29.167 and 30.397 for the fumarate, exo and endo adducts.

ii. (d) Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BBr_3/Al_2O_3(400°C) Complex for 10 Minutes Under Argon.

The Diels-Alder reaction of DMM and CP was performed under argon in the presence of BBr_3/Al_2O_3(400°C) complex. The reaction procedure, the amounts of reagents and BBr_3/Al_2O_3(400°C) complex, and the method used to analyze the product mixture were identical to that described in the General Procedure B, page 219. However, the reaction time was reduced to 10 minutes. GC retention time (min) were 29.139, 29.169 and 30.399 for the fumarate, exo and endo adducts. The yield of the

cycloadducts was 85.0%; the fumarate, exo and endo DMM adducts were formed in a 98:1:1 ratio.

iii. Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BCl_3/Al_2O_3(200°C) Complex.

The Diels-Alder reaction of DMM and CP was performed under argon in the presence of 10 grams of the BCl_3/Al_2O_3(200°C) complex. The reaction procedure, the amounts of reagents and the method used to analyze the product mixture were identical to that described in the General Procedure B for the reaction between DMM and CP in the presence of BBr_3/Al_2O_3(400°C) complex under argon, page 219. GC retention times (min) were 33.717, 34.045 and 35.121 for the fumarate, exo and endo adducts. The yield of the cycloadducts was 70.5%; the fumarate, exo and endo DMM adducts were formed in a 6:4:90 ratio.

iv. Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on BF_3/Al_2O_3(400°C) Complex.

The Diels-Alder reaction of DMM and CP was performed under argon in the presence of 10 grams of BF_3/Al_2O_3(400°C) complex. The reaction procedure, the amounts of reagents, and the method used to analyze the product mixture were identical to that described in the General Procedure B for the reaction between DMM and CP in the presence of BBr_3/Al_2O_3(400°C) complex under argon, page 219. GC retention times

(min) were 32.189, 33.012 and 34.288 for the fumarate, exo and endo adducts. The yield of the cycloadducts was 75.2%; the fumarate, exo and endo DMM adducts were formed in a 0:10:90 ratio.

v. Isomerization Study of Dimethyl Maleate on BBr_3/Al_2O_3 (400°C) Complex. General Procedure C.

10 grams of BBr_3/Al_2O_3 (400°C) was added to a 250 ml round bottom flask with a side arm. Dimethyl maleate (4 mmols) was added to the flask via syringe and the miture stirred for 3 minutes under argon. After this period, the mixture was quenched with 50 ml methanol and stirred for 1 hour. The products were then extracted with two 50 ml portions of diethyl ether and the solution removed from the solid by gravity filtration using a piece of fine grain filter paper. The diethyl ether and methanol were removed in vacuo at 40°C, and the products analyzed by GC/MS. Coinjection with known materials confirmed the products' identity. GC retention times (min) were 13.273 and 14.024 for DMM and DMF. In 3 minutes, 90.0% of DMM isomerized to DMF.

v (a) Isomerization Study of Dimethyl Maleate on BCl_3/Al_2O_3(200°C) Complex.

The isomerization study of dimethyl maleate on BCl_3/Al_2O_3(200°C) was carried out according to the procedure described in the General Procedure C for the isomerization of dimethyl maleate on BBr_3/Al_2O_3(400°C) complex above. GC retention time (min) were 13.228 and 14.102 for DMM and DMF. Only 5.0% of DMM isomerized to DMF after 15 minutes.

v. (b) Isomerization Study of Dimethyl Maleate on BF_3/Al_2O_3(400°C) Complex.

The isomerization study of dimethyl maleate on BF_3/Al_2O_3(400°C) were carried out according to the procedure described in the General Procedure C for the isomerization of dimethyl maleate on BBr_3/Al_2O_3(400°C) complex, page 223. GC retention time (min): 13.286 for DMM. DMM did not isomerize to DMF after 15 minutes.

vi. Diels-Alder Reactions of Methyl Acrylate and Isoprene with and without BBr_3/Al_2O_3(400°C) Complex.

vi. (a) Diels Alder Reaction of Methyl Acrylate and Isoprene in the Absence of solvent.

Methyl acrylate (0.01 mole) and then isoprene (0.01 mole) were added to a 250 ml round bottom flask with a sidearm via syringe. After 4 hours at room temperature under argon, the reaction mixture was analyzed according to the General Procedure B described for the reaction between DMM and CP on the BBr_3/Al_2O_3(400°C) complex, page 219. The ratio of the 1,3- and 1,4-disubstituted adducts was 15:85; the products were formed with an overall yield of 52.3%. GC retention times (min) were 13.546 and 13.779 for the 1,3-disubstituted and 1,4-disubstituted adducts, respectively.

vi (b) Diels Alder Reaction of Methyl Acrylate and Isoprene on BBr_3/Al_2O_3(400°C) Complex.

10 grams of BBr_3/Al_2O_3(400°C) complex were added to a 250 ml round-bottom flask with a side arm. Methyl acrylate (0.01 mole) was then added to the alumina by a syringe and the mixture stirred for 10 minutes under argon atmosphere. After the addition of 0.01 mole of isoprene, the mixture was stirred under argon for another 4 hours. Upon completion of the reaction, the mixture was quenched with 50 ml of methanol and stirred for 1 hour. The product mixture was analyzed by GC/MS according to the General Procedure B described for the reaction between DMM and CP on the BBr_3/Al_2O_3(400°C) complex, page 219. The 1,3-disubstituted and 1,4-disubstituted adducts were formed in was 10:90 ratio and in a 60.2% overall yield. GC retention times (min) were 14.781 and 14.734 for the 1,3-disubstituted and 1,4-disubstituted adducts, respectively.

vii. Diels Alder Reaction of Maleic Anhydride and Cyclopentadiene on BBr_3/Al_2O_3(400°C) Complex.

10 grams of BBr_3/Al_2O_3(400°C) complex was added to a 250 ml round bottom flask with a side arm. Maleic Anhydride (6 mmol) was then added to the reaction flask and the reaction mixture stirred for 10 minutes under argon. After the addition of 6 mmol of cyclopentadiene, the mixture was stirred under argon for another 4 hours. Upon completion of the reaction, the mixture was quenched with 50 ml of methanol and stirred for 1 hour. The product mixture was analyzed by GC/MS according to the

General Procedure B described for the reaction between DMM and CP on the BBr_3/Al_2O_3(400°C) complex, page 219. The yield of the endo cycloadduct was 35.0%; no exo adduct was formed. GC retention time (min) of the adduct was 17.129 min.

viii. Diels-Alder Reaction of Maleic Anhydride and Cyclopentadiene in Benzene.

Maleic anhydride (0.01 mole) in 10 ml of benzene and the CP (0.01 mole) were added into a 250 ml round bottom flask and stirred for 4 hours. Upon completition of the reaction, the benzene was removed in vacuo and the residue analyzed according to the General Procedure B described for the competition reaction between methyl acrylate and dimethyl maleate with cyclopentadiene on the BBr_3/Al_2O_3 (400°C) complex, page 219. The yield of the endo adduct was 35.0%. No exo adduct was formed. GC retention time (min) of the adduct was 17.129 min.

ix. Diels-Alder Reaction of Dimethyl Maleate and Cyclopentadiene on $SnCl_4/Al_2O_3$(400°C) Complex.

10 grams of $SnCl_4/Al_2O_3$(400°C) complex were added to a 250 ml round bottom flask with a side arm. Dimethyl maleate (6 mmol) was then added to the alumina by syringe injection and the mixture stirred for 10 minutes under argon atmosphere. After the addition of 6 mmol of cyclopentadiene, the reaction mixture was stirred under argon for another 4 hours. Upon completion of the reaction, the mixture was quenched with 50 ml of methanol and stirred for 1 hour. The product mixture was analyzed by GC/MS according to the General Procedure B described for the reaction between DMM and CP

on the BBr_3/Al_2O_3(400°C) complex, page 219. The fumarate, exo and endo adducts were formed in a 3:17:80 ratio with an overall yield of 54.5%. GC retention times (min) were 33.528, 34.001 and 35.010 for the fumarate, exo and endo adducts.

x. Diels Alder Reaction of Dimethyl Maleate and Cyclopentadiene On $TiCl_4/Al_2O_3$(400°C) Complex.

15 grams of $TiCl_4/Al_2O_3$(400°C) complex were added to a 250 ml round-bottom flask with a side arm. Dimethyl maleate (6 mmol) was then added to the alumina by syringe injection and the mixture stirred for 10 minutes under argon atmosphere. After the addition of 6 mmol of cyclopentadiene, the mixture was stirred under argon for another 4 hours. Upon completion of the reaction, the mixture was quenched with 50 ml of methanol and stirred for 1 hour. The product mixture was analyzed by GC/MS according to the General Procedure B described for the reaction between DMM and CP on the BBr_3/Al_2O_3(400°C) complex, page 219. The fumarate, exo and endo DMM adducts were formed in a 1:16:83 ratio with an overall yield of 50.3%. GC retention time (min) were 33.626, 34.011 and 35.089 for the fumarate, exo and endo adducts, respectively.

xi. Competitive Reaction of Methyl Acrylate and Dimethyl Maleate with Cyclopentadiene on BBr_3/Al_2O_3 (400°C). General Procedure D.

The following procedure was used for the reaction of DMM and CP on BBr_3/Al_2O_3 (400°C). The reaction was run on a scale of 4.0 mmol of each dienophile

and 5.0 mmol of cyclopentadiene for every 12.5 grams of unactivated alumina. Not all the reactions were performed on 12.5 grams of alumina, but the above ratios were maintained for all of the experiments. The methyl acrylate and dimethyl maleate were mixed together in a small vial. The mixture of the two dienophiles was added via syringe to a 250 ml round bottom flask with a sidearm containing the BBr_3/Al_2O_3 (400°C) under argon. After stirring the mixture of dienophiles on the alumina for 15 minutes using a magnetic stirrer, the cyclopentadiene was then added via a syringe, and the reaction mixture was stirred at room temperature for 4 hours. The reaction mixture was quenched with 50 ml of methanol and stirred for a least one hour. The products were extracted with two 50 ml portions of diethyl ether. The solution was separated from the solid by gravity filtration using a piece of fine grain filter paper. The diethyl ether and methanol were removed by evaporation at 40°C under vacuum. The previously tared round bottom flask was weighed to determine the total amount of reactants and products. The product was transferred to a vial, and a known amount of hexadecane was added as an internal standard for determining product yields. The amount of hexadecane used corresponded to a circa 50% yield of the products. The products were separated and analyzed by GC/MS, and the product yields determined by cutting and weighing the GC peaks obtained from the GC/MS. Known materials were coinjected to confirm the identity of the products. This competitive reaction resulted in a total of 14.05% of DMM adducts (14.05% fumarate, 0% exo and 0% endo DMM adducts) and a total of 7.35% of MA adducts (0.94% exo and 6.41% endo MA adduct): GC retention times were exo MA adduct (10.833 min); endo MA adduct (11.329 min);

fumarate adduct (28.029 min); exo DMM adduct (29.276 min); endo DMM adduct (29.998 min).

xi. (a) Competitive Reaction between Methyl Acrylate (MA) and Dimethyl Maleate(DMM) with Cyclopentadiene on BBr_3/Al_2O_3 (300°C).

The competition reaction of MA and DMM with CP in the presence of BBr_3/Al_2O_3 (300°C) was carried out according to the procedure described in the General Procedure D, page 227. The competitive reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmol of cyclopentadiene for every 12.5 grams of unactivated alumina. The products obtained from this competition reaction were analyzed by GC/MS and the product yields determined by cutting and weighing the GC peaks following the procedure used in the General Procedure D. Analysis of the product mixture showed a total of 65.83% DMM adducts (65.83% fumarate, 0% exo and 0% endo DMM adducts) and a total of 25.70% MA adducts (3.67% exo and 22.03% endo MA adducts). GC retention times were exo MA adduct (11.012 min); endo MA adduct (11.146 min); fumarate adduct (28.447 min).

xi. (b) Competitive Reaction Between Methyl Acrylate (MA) and Dimethyl Maleate (DMM) for Cyclopentadiene (CP) on BBr_3/Al_2O_3(200°C).

This reaction was carried out according to the General Procedure D described for the reaction of MA and DMM with CP on the BBr_3/Al_2O_3(400°C) complex on page 227. Analysis of the product mixture showed a total of 52.22% DMM adducts (52.22%

fumarate, 0% exo and 0% endo DMM adducts). GC retention time (min) were exo MA adduct (11.012 min); endo MA adduct (11.168 min); fumarate adduct (28.424 min).

xi. (c) Competitive Reaction between Methyl Acrylate (MA) and Dimethyl Maleate (DMM) for Cyclopentadiene (CP) on BBr_3/Al_2O_3(100°C).

This reaction was carried out according to the General Procedure D described for the reaction of MA and DMM with CP on the BBr_3/Al_2O_3(400°C) complex on page 227. Analysis of the product mixture showed a total of 63.52% DMM adducts (63.52% fumarate, 0% exo and 0% endo DMM adducts) and a total of 20.81% MA adducts (2.43% exo and 18.38% endo MA adducts). GC retention time were exo MA adduct (10.883 min); endo MA adduct (11.329 min); DMF adduct (28.029 min); exo DMM adduct (29.276 min); endo DMM adduct (29.998 min).

xi. (d) Competitive Reaction between Methyl Acrylate and Dimethyl Maleate for Cyclopentadiene on BBr_3/Al_2O_3(Unactivated).

The competition reaction between MA and DMM for CP was performed in the presence of the BBr_3/Al_2O_3(Unactivated) complex. The rection procedure, the amounts of reagents and the method to analyze the product mixture were identical to the General Procedure D described for the reaction of MA and DMM with CP on the BBr_3/Al_2O_3(400°C) complex, page 227. Analysis of the product mixture showed a total of 49.72% DMM adducts (45.81% fumarate, 1.03% exo and 2.88% endo DMM adducts) and a total of 13.55% MA adducts (1.8% exo and 11.74% endo MA adducts).

GC retention time (min) were exo MA adduct (10.882 min); endo MA adduct (11.327 min); DMF adduct (28.027 min); exo DMM adduct (29.275 min); endo DMM adduct (29.989 min).

xii. Competitive Reaction between Methyl Acrylate and Dimethyl Fumarate for Cyclopentadiene on BBr_3/Al_2O_3 (400°C) Complex. General Procedure E.

The reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmol of cyclopentadiene and 12.5 grams of unactivated alumina. The dimethyl fumarate was first dissolved in a minimum amount of diethyl ether (approximately 70 ml for every 1.441 grams of dimethyl fumarate). After dissolving the methyl acrylate in the solution, it was then added to the BBr_3/Al_2O_3 (400°C) complex under argon. After stirring for 15 minutes, the diethyl ether was removed in vacuo at a pressure of 0.5 mm Hg for 1 to 1.5 hours. After the solid was placed under argon, the cyclopentadiene was added via a syringe and the reaction mixture stirred at room temperature for 4 hours. The reaction was then quenched with 50 ml of methanol and stirred for an additional one hour. The reaction mixture was then worked up and analyzed by GC/MS. Analysis of the product mixture showed a 70.5% yield of DMF adduct and 0% MA adducts. GC retention time of DMF adduct = 26.310 min.

xii. (a) Competitive Reaction between Methyl Acrylate (MA) and Dimethyl Fumarate (DMF) for Cyclopentadiene (CP) on BBr_3/Al_2O_3(200°C) Complex.

The competition reaction of MA and DMF with CP was performed in the presence of the BBr_3/Al_2O_3(200°C) complex using the competition rection procedure, the amounts of reagents and the method to analyze the product mixture as described in General Procedure E, page 231. Analysis of the product mixture showed a 58.80% DMF adduct and 0% MA adducts. GC retention time for the DMF adduct = 29.716 min.

vii. (b) Competitive Reaction between Methyl Acrylate (MA) and Dimethyl Fumarate (DMF) for Cyclopentadiene (CP) on BBr_3/Al_2O_3(Unactivated) Complex.

The competition reaction of MA and DMF with CP was performed in the presence of the BBr_3/Al_2O_3(unactivated) complex. The competition procedure, the amounts of reagents, and the method to analyze the product mixture were identical to that described on General Procedure E, page 231. Analysis of the product mixture showed a 22.02% yield of DMF adduct and 0% yield of MA adduct. GC retention time for the DMF adduct = 29.124 min.

xiii. Competition Reaction between Dimethyl Maleate and Dimethyl Fumarate for Cyclopentadiene on BBr_3/Al_2O_3 (400°C) Complex.

The reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmol of cyclopentadiene and 12.5 grams of unactivated alumina. The dimethyl fumarate was

dissolved in a minimum amount of diethyl ether (approximately 70 ml for 1.441 grams of dimethyl fumarate). After dissolving the DMM in the solution, the resulting solution was added to the BBr_3/Al_2O_3 (400°C) complex under argon and was stirred for 15 minutes. The diethyl ether was then removed in vacuo at room temperature under 0.5 mm Hg of pressure. After placing the alumina under argon after evaporation of the ether, the cyclopentadiene was added via a syringe, and the resulting reaction mixture stirred at room temperature for 4 hours. The reaction was then quenched with 50 ml of methanol and was stirred for additional one hour. The reaction mixture was worked up and analyzed by GC/MS. Analysis of the product mixture showed 0% of the DMM adduct and 43.24% of the DMF adduct. GC retention time for the DMF adduct = 26.311 min.

xiii. (a) Competitive Reaction of Dimethyl Maleate (DMM) and Dimethyl Fumarate (DMF) with Cyclopentadiene (CP) on BBr_3/Al_2O_3(200°C) Complex.

The competition reaction of DMM and DMF with CP was performed on the BBr_3/Al_2O_3(200°C) complex. The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed 0% of the DMM adduct and 24.02% of the DMF adduct. GC retention time for the DMF adduct (29.652 min).

xiii. (b) Competitive Reaction between Dimethyl Maleate (DMM) and Dimethyl Fumarate (DMF) for Cyclopentadiene (CP) on BBr_3/Al_2O_3(Unactivated) Complex.

The competition reaction of DMM and DMF with CP was performed in the presence of the BBr_3/Al_2O_3(unactivated) complex. The competition procedure, the amounts of reagents, and the method to analyze the product mixture were identical to that of the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed 0% of the DMM adduct and 32.82% of the DMF adduct. GC retention time for the DMF adduct = 33.717 min.

xiv. Competitive Reaction between Methyl Acrylate and Dimethyl Maleate for Cyclopentadiene on Al_2O_3 (400°C).

The following procedure was used for the competition reaction of methyl acrylate and dimethyl maleate on Al_2O_3 (400°C). The reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmol of cyclopentadiene for every 12.5 grams of unactivated alumina. Other competition reactions were performed on different amounts of alumina, but the above ratio were maintained for all of the experiments. The methyl acrylate and dimethyl maleate were mixed together in a small vial. The mixture of the two dienophiles was added via syringe to a 250 ml round bottom flask with sidearm containing the Al_2O_3 (400°C) under argon. After stirring the alumina for 15 minutes using a magnetic stirrer, the cyclopentadiene was added via a syringe, and the resulting reaction mixture stirred at room temperature for 4 hours. The reaction mixture was

quenched with 50 ml of methanol and stirred for at least one hour. The products were extracted with two 50 ml portions of diethyl ether. The solution was separated from the solid by gravity filtration and removed in vacuo at 40°C. The tared round bottom flask were weighed to determine the total weight of the products. The products were transferred to a vial and a known amount of hexadecane added as an internal standard for determining the product yields. The amount of hexadecane used corresponded to circa 50% yield of the products. The products were analyzed by GC/MS, and the product yields determined by cutting and weighing the GC peaks obtained from the GC/MS spectrum. Analysis of the product mixture showed a total of 26.49% of the DMM adducts (0.26% exo and 26.23% endo DMM adduct) and a total of 16.22% MA adducts (2.27% exo and 13.95% endo MA adduct). GC retention times = exo MA adduct (11.020 min); endo MA adduct (11.554 min); DMF adduct (29.137 min); exo DMM adduct (29.168 min); endo DMM adduct (30.398 min).

xiv. (a) Competitive Reaction between Methyl Acrylate and Dimethyl Maleate with Cyclopentadiene on Alumina Activated at 300°C [Al_2O_3(300°C)].

The competiton reaction of DMM and DMF with CP was performed in the presence of the Al_2O_3(300°C). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA with DMF and CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed 44.03% of DMM adducts (2.20% exo and 41.83% endo DMM adduct) and 78.92% of MA

adducts (14.21% exo and 64.71% endo MA adduct). GC retention times = endo MA adduct (11.675 min); endo DMM adduct (28.972 min).

xiv. (b) Competitive Reaction of Methyl Acrylate (MA) and Dimethyl Maleate (DMM) with Cyclopentadiene (CP) on Alumina Activated at 200°C [Al_2O_3(200°C)].

The competition reaction of DMM and DMF with CP was performed in the presence of the Al_2O_3(200°C). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 96.43% of DMM adducts (14.46% exo and 81.97% endo DMM adduct) and 64.56% of MA adducts (11.62% exo and 52.94% endo MA adduct). GC retention times = exo MA adduct (12.835 min), endo MA adduct (13.357 min); exo DMM adduct (31.556 min) endo DMM adduct (32.801 min).

xiv. (c) Competitive Reaction of Methyl Acrylate (MA) and Dimethyl Maleate (DMM) with Cyclopentadiene (CP) on Alumina Activated at 100°C (Al_2O_3/100°C).

The competition reaction of DMM and DMF with CP was performed in the presence of the Al_2O_3/100°C. The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total

of 18.37% of DMM adducts (2.76% exo and 15.61% endo DMM adduct) and a total of 24.68% of MA adducts (7.40% exo and 17.28% endo MA adduct). GC retention times = exo MA adduct (11.403 min), endo MA adduct (11.519 min); exo DMM adduct (28.201 min) endo DMM adduct (29.994 min).

xiv. (d) Competitive Reaction of Methyl Acrylate (MA) and Dimethyl Maleate (DMM) with Cyclopentadiene (CP) on Unactivated Alumina [Al_2O_3(Unactivated)].

The competition reaction of DMM and DMF with CP was performed in the presence of the Al_2O_3(unactivated). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 59.89% DMM adducts (9.67% exo and 47.22% endo DMM adduct) and a total of 24.33% MA adducts (7.30% exo and 17.03% endo MA adduct). GC retention times = exo MA adduct (12.836 min), endo MA adduct (13.328 min); fumarate adduct (30.450 min); exo DMM adduct (31.539 min) endo DMM adduct (32.734 min).

xv. Competitive Reaction of Methyl Acrylate and Dimethyl Fumarate with Cyclopentadiene on Al_2O_3 (400°C) Complex.

The reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmols of diene and 12.5 grams of unactivated alumina. The dimethyl fumarate was first dissolved in a minimum amount of diethyl ether (approximately 70 ml for every 1.441

grams of dimethyl fumarate), and then the methyl acrylate was dissolved in this solution. The solution was then added with stirring to the Al_2O_3 (400°C) under argon. After 15 minutes, the diethyl ether was removed in vacuo at room temperature at a pressure of 0.5 mm Hg for 1 to 1.5 hours. After the solvent was removed, the reaction mixture was placed under argon and the cyclopentadiene was added via a syringe. The reaction mixture was stirred at room temperature for 4 hours at room temperature. The reaction was then quenched with 50 ml of methanol and stirred for at least one hour. The reaction mixture was then worked up and analyzed according to the General Procedure E described for the competition reaction of methyl acrylate and dimethyl maleate with cyclopentadiene on the BBr_3/Al_2O_3 (400°C) complex, page 231. Analysis of the product mixture showed 5.78% of the DMF adduct and a total of 3.82% MA adducts (0.04% exo and 3.78% endo adduct). GC retention times = endo MA adduct (10.209 min); DMF adduct (29.033 min).

xv. (a) Competitive Reaction of Methyl Acrylate (MA) and Dimethyl Fumarate (DMF) with Cyclopentadiene (CP) on Alumina Activated at 200°C[Al_2O_3(200°C)].

The competition reaction of DDM and DMF with CP was performed in the presence of the Al_2O_3(200°C). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed 30.46% of the DMF adduct and a total of 57.44% MA adducts (1.15% exo and 56.29% endo

MA adduct). GC retention times = exo MA adduct (14.699 min); endo MA adduct (14.825 min); DMF adduct (33.557 min).

xv. (b) Competitive Reaction of Methyl Acrylate (MA) and Dimethyl Fumarate (DMF) with Cyclopentadiene (CP) on Unactivated Alumina [Al_2O_3(Unactivated)].

The competition reaction of DDM and DMF with CP was performed in the presence of the Al_2O_3(Unactivated). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed 7.48% of the DMF adduct and a total of 9.52% MA adducts (1.90% exo and 7.62% endo MA adduct). GC retention times = exo MA adduct (10.299 min); endo MA adduct (10.358 min); DMF adduct (30.689 min).

xvi. Competitive Reaction of Dimethyl Maleate and Dimethyl Fumarate with Cyclopentadiene on Al_2O_3 (400°C) Complex.

The reaction was run on a scale of 4.0 mmol of each dienophile and 5.0 mmoles of cyclopentadiene and 12.5 grams of unactivated alumina. The dimethyl fumarate was first dissolved in a minimum amount of diethyl ether (approximately 70 ml of 1.441 grams of dimethyl fumarate), and then the dimethyl maleate was added to the ether solution. After adding the solution to the BBr_3/Al_2O_3 (400°C) complex under argon, the diethyl ether was then removed in vacuo at room temperature at 0.5 mm Hg of pressure.

The alumina mixture was placed under argon and the cyclopentadiene was added via a syringe, and the reaction mixture was stirred at room temperature for 4 hours. The reaction was then quenched with 50 ml of methanol and was stirred for one additional hour. The reaction mixture was worked up and analyzed accroding to the General Procedure E described for the competition reaction of methyl acrylate and dimethyl maleate with cyclopentadiene on the BBr_3/Al_2O_3 (400°C) complex, page 231. Analysis of the product mixture showed a total of 48.21% DMM adducts (13.50% exo and 34.71% endo DMM adducts) and 50.11% DMF adduct. GC retention times = DMF adduct (29.427 min); exo DMM adduct (29.643 min); endo DMM adduct (30.413 min).

xvi. (a) Competitive Reaction of Dimethyl Maleate and Dimethyl Fumarate with Cyclopentadiene on Alumina Activated at 200°C [Al_2O_3(200°C)].

The competition reaction of DDM and DMF with CP was performed in the presence of the Al_2O_3/200°C. The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 48.30% DMM adducts (14.97% exo and 33.33% endo DMM adduct) and 49.82% DMF adduct. GC retention times = DMF adduct (34.025 min); exo DMM adduct (34.290 min); endo DMM adduct (35.122 min).

xvi. (b) Competitive Reaction of Dimethyl Maleate and Dimethyl Fumarate with Cyclopentadiene on Unactivated Alumina. [Al_2O_3(unactivated)].

The competition reaction of DDM and DMF with CP was performed in the presence of the Al_2O_3(unactivated). The competition procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 48.85% DMM adducts (14.54% exo and 33.92% endo) and 49.50% DMF adduct. GC retention times = DMF adduct (29.353 min); exo DMM adduct (29.622 min); endo DMM adduct (30.395 min).

xvii. Competitive Reaction of Methyl Acrylate and Dimethyl Maleate with Cyclopentadiene on 2 mmol BBr_3/g Al_2O_3(400°C) Complex.

The competition reaction of DDM and DMF with CP was performed in the presence of 2 mmol BBr_3/gAl_2O_3/400°C. The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF and CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 10.97% DMM adducts (5.44% fumarate, 0% exo and 5.23% endo DMM adducts) and a total of 11.16% MA adducts (1.67% exo and 9.49% endo MA adducts). GC retention times were exo MA adduct (10.882 min); endo MA adduct (11.328 min); DMF adduct (28.028 min); exo DMM adduct (29.274 min); endo DMM adduct (29.997 min).

xviii. Competitive Reaction of Methyl Acrylate and Dimethyl Maleate with Cyclopentadiene (CP) on 3 mmol BBr_3/g Al_2O_3(400°C) Complex.

The competition reaction of DMM and DMF with CP was performed in the presence of 3 mmol BBr_3/g Al_2O_3(400°C). The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure E described for the reaction of MA and DMF with CP on the BBr_3/Al_2O_3(400°C) complex, page 231. Analysis of the product mixture showed a total of 14.53% DMM adducts (7.08% fumarate, 0% exo and 7.45% endo DMM adducts) and a total of 15.36% MA adducts (2.76% exo and 12.60% endo MA adducts). GC retention times were exo MA adduct (10.882 min); endo MA adduct (11.328 min); DMF adduct (28.028 min); exo DMM adduct (29.275 min); endo DMM adduct (29.998 min).

xix. Competitve Reaction of Methyl Acrylate and Dimethyl Maleate with Cyclopentadiene in Solution.

4 mmol of each dienophile was dissolved in 50 ml of diethyl ether in air. After stirring the solution for 15 minutes, cyclopentadiene 5.0 mmoles was added to the reaction mixture via syringe and the resulting reaction stirred at room temperature for 4 hours. The ether was removed in vacuo at room temperature. The product was analyzed according to the General Procedure D described for competition reaction of methyl acrylate and dimethyl maleate with cyclopentadiene on the BBr_3/Al_2O_3 (400°C) complex, page 227. Analysis of the product mixture showed a total of 17.76% DMM adducts (2.43% exo and 15.85% endo DMM adducts) and a total of 12.94% MA adducts

(4.40% exo and 8.54% endo MA adducts). GC retention times were exo MA adduct (10.883 min); endo MA adduct (11.329 min); exo DMM adduct (29.276 min); endo DMM adduct (29.999 min).

xx. Competitive Reaction of Methyl Acrylate and Dimethyl Fumarate with Cyclopentadiene in Solution.

The competition reaction of MA and DMF with CP was performed in 15 mL of diethyl ether instead of alumina or BBr_3/Al_2O_3. The reaction procedure, the amounts of reagents, and the method to analyze the product mixture were carried out according to the General Procedure D described for the reaction MA and DMM with CP on the BBr_3/Al_2O_3(400°C) complex, page 227. Analysis of the product mixture showed a total of 77.77% DMM adducts and a total of 59.60% MA adducts (14.90% exo and 44.70% endo MA adducts). GC retention times were exo MA adduct (10.882 min); endo MA adduct (11.328 min) and DMF adduct (28.028 min).

xxi. Competitive Reaction of Dimethyl Maleate and Dimethyl Fumarate with Cyclopentadiene in Solution.

The competition reaction of DMM and DMF with CP was performed in 15 mL diethyl ether. The reaction procedure, the amounts of reagents, and the method to analyse the product mixture were identical to that in the General Procedure D described for the reaction MA and DMM with CP on the BBr_3/Al_2O_3(400°C) complex, page 227.

Analysis of the product mixture showed 0% DMM adducts and 9.79% DMF adducts.

GC retention time for the DMF adduct = 28.028 min.

REFERENCES

1. Diels, O.; Alder, K. *Liebigs. Ann. Chem.* **1928**, *98*, 460.
2. Onishenko, A. S. *Diene Synthesis*, Israel Program for Scientific Translations. Jersalem: **1964**.
3. Ege, S. N. *Organic Chemistry, 2nd Edition*, Heath and Co., Massachusetts: **1989**.
4. Vollhardt, K. P. C. *Organic Chemistry*, Freeman, New York: 1987, p. 591.
5. Wade, L. G. *Organic Chemistry*, Prentice-Hall, New Jersey: 1991, p. 651.
6. Isaacs N. S.; *Physical Organic Chemistry*, Longman Scientific & Technical Co., Longman, U.K.: pg 661, **1987**.
7. Grieco, P. A.; Nunes, J. J.; Gaul, M. D. *J. Am. Chem. Soc.* **1990**, *112*, 4595.
8. Parlar, H.; Baumannm R. *Angew. Chem. Int. Ed. Engl.* **1981**, *20*, 1014.
9. (a) Yates, P.; Eaton, P. *J. Am. Chem. Soc.* **1960**, *82*, 4436.
   (b) Hondrogiannis, G.; Pagni, R. M.; Kabalka, G. W.; Anosike, P.; Kurt, R. *Tetrahedron Lett.* **1990**, *31*, 5433.
10. (a) Lamy Schelkens, H.; Gioni, D.; Ghosez, L. *Tetrahedron Lett.* **1989**, *30*, 5887.
    (b) Maruoka, K.; Yamamoto, H. *J. Am. Chem. Soc.* 1989, 111, 789-790.
    (c) Midland, M. M.; Alfonso, M. M. *J. Am. Chem. Soc.* **1989**, 111, 4368.
    (d) Narasaka, K.; Iwasawa, N.; Inoue, M.; Yamada, T.; Nakashima, N.; Sugimori, J. *J. Am. Chem. Soc.* **1989**, *111*, 5340.

(e) Corey, R.; Imwinkelried, E. J.; Pikul, S. Xiang, Y. B. *J. Am. Chem. Soc.* **1989**, *111*, 5493.

11. Douglas, B. E.; McDaniel, D. H.; *Concepts and Models of Inorganic Chemistry*, Blaisdell Pub. Co., New York: **1965**, 212.

12 Friguelli, F.; Taticchi, A.; *Dienes in the Diels-Alder Reaction*, Wiley-Interscience Pub., New York; **1990**.

13. Dean, J.A.; *Lange's Handbook of Chemistry*, 13th ed., McGraw-Hill Inc., New York: **1985**,

14. Bains, S.; Pagni, R. M.; Kabalka, G. W. *Tetrahedron Lett.* **1991**, 5663.

15. Laszlo, P.; Lucchetti, J. *Tetrahedron Lett.* **1984**, *25*, 2147.

16. Inukai, T.; Kojima, T. *J. Org. Chem.* **1967**, *32*, 872.

17. Sauer, J.; Wiest, H. and Mielert, A; *Z. Naturforch*, **1962**, 17b, 203.

18. Titov, J. A. *Russ. Chem. Rev.*, English Transl, **1962**, 267.

19. I would like to acknowledge Green, J.F. and Chang, J-L. for their assistance.

20. Gaetano, K.; Pagni, R. M.; Kabalka, G. W.; Bridwell, P.; Walsh, E.; True, J. Underwood, M. *J. Org. Chem.* **1985**, 50, 499.

Vita

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