

Investigating the Phosphorus-30 Proton Capture Reaction in Classical Novae

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To Ellie and Newton...

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Abstract

Accurate modeling of classical nova nucleosynthesis is fundamentally dependent on the thermonuclear reaction rates of the nuclei involved. In particular, it has been shown that the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate is the largest remaining source of uncertainty in the final abundances of nuclei created in a classical nova involving an ONe white dwarf. Currently, a direct measurement of the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction is not experimentally feasible. Previous attempts at constraining the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate have been made using the Hauser-Feshbach statistical approach to calculate the cross section. However, the level density in ^{31}S may not be sufficiently high for this approach. A more accurate calculation can be made by assuming the reaction proceeds via narrow and isolated resonances. Considering the contribution from individual resonant states, the calculation of the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate at nova temperatures requires knowledge of the spin and parity assignments and resonance strengths of the levels in ^{31}S just above the proton threshold. To obtain the relevant nuclear data, a measurement of the $^{32}\text{S}(\text{p},\text{d})^{31}\text{S}^*$ reaction has been performed at the Texas A&M Cyclotron Institute using a proton beam from the K150 cyclotron and a target consisting of ZnS deposited on a thin carbon backing. The particle-gamma array, Hyperion, was used in a configuration with a dE-E telescope of silicon detectors downstream of the target position for the detection of direct reaction products, and a single silicon detector placed upstream of the target for the detection of decay protons.

In this experiment states above the proton separation energy in ^{31}S were populated via the $^{32}\text{S}(\text{p},\text{d})^{31}\text{S}^*$ reaction. A single proton unbound state was observed to decay via γ -ray emission, and several states were observed to decay by proton emission. New analysis techniques for measuring angular correlations between reaction products and decay protons

were developed. Branching ratios and constraints on the angular momentum of decays for several proton emitting states are presented. The impact of the new data on the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate is assessed. Finally, a discussion of the challenges encountered in this experiment and a proposal for a follow-up experiment to mitigate these challenges is presented.

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Chapter 1

Introduction and Motivation

1.1 Stellar Evolution

The life and death of a star are inextricably linked to nuclear physics. Nuclear reactions provide the energy that powers all stars and it is the products of these reactions that drive stellar evolution. All stars begin their life with the fusion of hydrogen into helium, known as hydrogen burning. As a star evolves, it can advance through various stages of nuclear burning involving reactions with increasingly heavy nuclei before exhausting its fuel and ceasing to generate energy. The number of burning stages a star reaches during its life depends on its initial mass, with more massive stars reaching more advanced stages of burning at the end of their life.

The formation of a star begins when a molecular cloud in the interstellar medium is perturbed and contracts due to gravitational forces, and becomes very dense. The gravitational potential energy is converted into thermal energy and eventually the gas reaches a sufficiently high temperature to initiate hydrogen burning ($\sim 1\text{-}2 \times 10^7$ K) [15]. The energy generated from hydrogen burning at the center of the star provides outward radiation pressure that supports the star from further gravitational contraction and an equilibrium state is reached.

1.1.1 Stages of Nuclear Burning

As mentioned above, hydrogen burning is the first stage of burning in a star. Stars which are in this stage are known as main-sequence stars. Our Sun is currently a main-sequence star. Hydrogen burning occurs in two major ways, the proton-proton chain (p-p chain) and the carbon-nitrogen-oxygen cycle (CNO cycle), depending on the temperature [16]. The details of the individual reactions involved in the the p-p chain and CNO cycle are beyond the scope of this dissertation, but it should be understood that both processes convert hydrogen into helium and release energy. As hydrogen burning proceeds, helium builds up inside the core of the star.

The helium core is not generating energy at this point and therefore can not support itself. The core begins to contract, which causes it to further heat up due to gravitational energy being converted in to thermal energy. Hydrogen burning continues in a shell surrounding the helium core. The increase in the temperature of the core causes the outer layers, still mostly comprised of hydrogen, to expand, and the star swells in size. The increased size of the star causes it to become more luminous. The outer layers become relatively cool causing the star to appear more red in color. The star has now left the main-sequence and entered what is known as the red giant branch phase.

When the core reaches a critical temperature and density, helium nuclei can begin to fuse and a new stage of nuclear burning begins. This stage of nuclear burning is known as helium burning. The main reaction that powers helium-burning is the triple-alpha process in which three helium nuclei fuse to become carbon and release energy [17]. In addition to the triple-alpha process, once some carbon has built up in the star, carbon nuclei will capture helium nuclei to produce oxygen. As helium burning progresses, carbon and oxygen build up in the core of the star. The helium burning is now confined to a shell surrounding the carbon and oxygen core. There is also a shell outside of the helium-burning region where hydrogen-burning is still taking place. At this point, stars with a mass less than ~ 8 solar masses ($M_{\odot}$) will enter what is known as the asymptotic giant branch (AGB) phase. During this phase the star will undergo periods of intense helium-burning known as helium shell

flashes. The star will swell to an even larger size and the outer atmosphere will cool. The radiation pressure from the helium burning shell drives a flow of mass from the outer layers into the interstellar medium. Stars in the AGB phase will eventually lose large fractions of their mass in this way. The remaining core of the AGB star cools to become a white dwarf.

For stars with masses in the $\sim 8\text{-}10$ solar mass ($M_{\odot}$) range, the carbon and oxygen core will eventually reach a high enough temperature and density for carbon nuclei to begin fusing and the carbon-burning phase begins. The main product of carbon burning is neon. Trace amounts of sodium and magnesium will also be produced during carbon burning. For more massive stars ($\gtrsim 10 M_{\odot}$) burning stages beyond carbon-burning will occur. These stars will eventually lead to a supernova, leaving behind a neutron star or black hole and are not the focus of this work.

1.1.2 White Dwarfs

White dwarfs are remnants of low and medium mass stars ($\lesssim 10 M_{\odot}$) which have ceased to burn their nuclear fuel. As a star in this mass range nears the end of its life, the core, which is no longer producing energy, is not generating the radiation pressure required to support itself against gravitational collapse. The collapse of the core is eventually halted when the matter becomes degenerate, and the core is then supported from further collapse by the electron degeneracy pressure. During the AGB phase, the outer layers of the star are shed, and the degenerate core that is left behind becomes a white dwarf.

The matter inside a white dwarf is completely ionized and therefore consists of a sea of free electrons with the positive ions mixed in [18]. As a stellar core contracts, the electrons are forced into occupying all of the lowest available energy states. The Pauli exclusion principle does not allow two identical fermions to occupy the same quantum state simultaneously. Electrons will eventually be forced into states with more energy than the thermal energy of the gas and therefore the gas becomes degenerate. The white dwarf resists further compression due to the electrons being unable to move to already occupied quantum

states. The pressure of a degenerate gas does not depend on the temperature like a classical ideal gas. Instead the pressure is related to the density of the gas.

An interesting result of the equation of state for degenerate matter depending on the density of the gas instead of the temperature is the mass-radius relationship for white dwarfs. Counter-intuitively, as the mass of a white dwarf increases its radius decreases. It was shown by E.C. Stoner [19] and S. Chandrasekhar [20] that this leads to a limiting mass for a white dwarf. This mass limit is now known as the Chandrasekhar limit and has a value of $1.44 M_{\odot}$ for a white dwarf composed of ^{12}C and ^{16}O .

White dwarfs can be grouped into three categories based on their composition: helium, carbon-oxygen (CO), and oxygen-neon (ONe) white dwarfs. The difference in composition is directly related to the final nuclear burning stage, and hence the mass, of the original star. Stars with relatively low mass, around $0.5 M_{\odot}$, will never reach the temperature and density required to initiate the triple-alpha process and will therefore stop producing energy once they have exhausted all of the hydrogen fuel in the core. In theory, these stars will end their life comprised almost entirely of helium and become helium white dwarfs. However, a star with such a low mass would take much longer than the age of the universe to exhaust its hydrogen fuel and therefore this is not the source of known helium white dwarfs. Observations of helium white dwarfs indicate that they originate in close binary systems and are the result of mass transfer from one of the stars to its companion [21]. If the star loses enough mass prior to helium ignition to prevent the core from ever becoming hot enough to initiate helium burning, then eventually a helium core in which no nuclear burning is taking place will be left behind.

Stars with an initial mass between $\sim 0.5\text{--}8 M_{\odot}$ will have been able to produce carbon and oxygen. During the asymptotic giant branch phase, the star will expel its outer layers, leaving behind the core of carbon and oxygen. The remaining core becomes a carbon-oxygen (CO) white dwarf. Finally, stars with an initial mass between $\sim 8\text{--}10 M_{\odot}$ are able to fuse carbon towards the end of nuclear burning. As mentioned in the previous section, the products of carbon burning are neon, sodium, and magnesium, with neon being the most abundant.

The core of a star of this mass will never reach the temperature required to fuse oxygen, and therefore most of the oxygen remains present. These stars will also enter the AGB phase, during which they will shed their outer layers leaving behind a core comprised of mostly oxygen and neon. The remaining core, once cooled, is called an oxygen-neon (ONe) white dwarf. It should be noted that there are trace amounts of magnesium and silicon in ONe white dwarfs which were produced via the $^{20}\text{Ne}(^4\text{He},\gamma)^{24}\text{Mg}$ and $^{24}\text{Mg}(^4\text{He},\gamma)^{28}\text{Si}$ reactions respectively. The presence of these heavier nuclei will become important later when discussing nucleosynthesis in classical novae.

1.2 Classical Novae

Classical Novae are explosive nuclear burning events that can occur in binary star systems where one of the stars has advanced through its life cycle and becomes a white dwarf, while its companion remains a main sequence star. About one half of all stars like the sun are in binary systems [22]. If the orbital separation of the two stars is small enough, as the companion star progresses off the main sequence and swells in size it may overflow its Roche lobe causing hydrogen-rich material from its atmosphere to fall onto the white dwarf. (See Figure 1.1) The Roche lobe is the region around a star in a binary system in which material is gravitationally bound to the star. The Roche lobes of the two stars in the binary system meet at the L1 Lagrange point where the gravitational attraction of the two stars and the centripetal acceleration of the system cancel each other out.

This material accretes on the surface of the white dwarf and mixes, by processes that are not well understood, with the heavier elements present in the underlying white dwarf. The accreted material is heated by gravitational compression and nuclear fusion. However, the bottom layer of the accreted material becomes electron degenerate and therefore does not expand even as the temperature increases [23]. Eventually, the temperature reaches the Fermi temperature and the degeneracy is lifted, however at this point the temperature is increasing so rapidly that a thermonuclear runaway (TNR) begins. The TNR causes an explosion that ejects nuclear processed material from the accreted envelope into the interstellar medium.

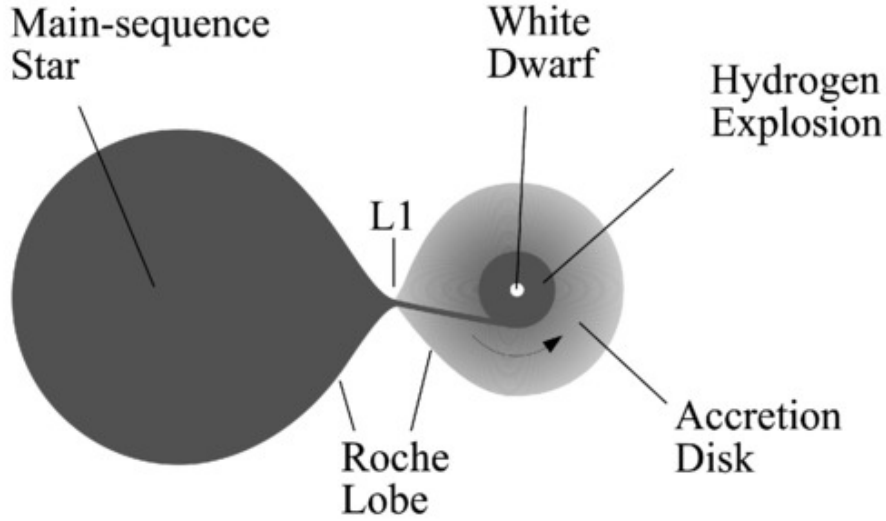


Figure 1.1: Schematic of a close binary system in which a main-sequence star has overflown its Roche lobe resulting in Hydrogen-rich material being accreted onto the surface of the companion white dwarf.[5]

Two images of Nova Cygni 1992, taken 7 months apart, can be seen in Figure 1.2. In these images it is possible to see the ejected envelope expanding out into space. Typical timescales for the TNR are on the order of a few hundred seconds[23].

The peak temperature of a nova event depends on the mass of the white dwarf, and ranges from 0.1 - 0.4 GK [23]. More massive white dwarfs have smaller radii, and therefore are more dense. The Fermi temperature of a degenerate gas scales with the density of the gas. Meaning a more dense white dwarf will have a larger Fermi temperature. Therefore, material accreted onto a more massive white dwarf reaches a higher temperature before the degeneracy is lifted and the material is ejected into the interstellar medium.

The characteristics of a classical nova explosion fundamentally depend on the rates of the nuclear reactions involved. In addition, the mass and composition of the white dwarf, the composition of the accreted material, the rate of accretion, and the degree of mixing between the accreted material and white dwarf material will also play a role in determining the specifics of the explosion [24]. In this work we are focused on constraining the thermonuclear rate of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ proton capture reaction, which has been shown to be of particular

Nova Cygni 1992
Hubble Space Telescope
Faint Object Camera

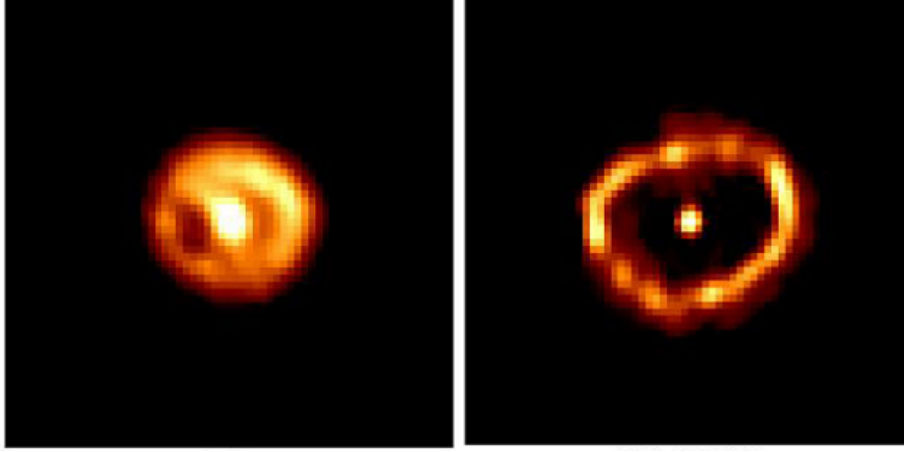


Figure 1.2: Observations of the Cygni 1992 Nova using the Hubble Space Telescope’s faint object camera. The two images were taken approximately 7 months apart. The “bubble-like” structure of the ejected material has expanded over time. (Image credit: F. Paresce, R. Jedrzejewski (STScI), NASA and ESA)

importance for the interpretation of several observables that provide information about the physics of white dwarfs and classical novae [25].

1.2.1 Nova Nucleosynthesis

During the TNR, there are many nuclear reactions that occur in addition to the fusion reactions of the pp-chain and the CNO cycle. Due to the mixing of the accreted hydrogen-rich material and material from the underlying white dwarf, there are significant quantities of heavier elements present in the region where the TNR occurs [25]. The mechanism and timing of this mixing remains one of the fundamental puzzles of the classical nova problem. Three-dimensional nuclear hydrodynamical simulations have suggested that mixing is driven by Kelvin-Helmholtz instabilities arising at the interface of the accreted material and the white dwarf during the onset of the TNR [26]. Regardless of the exact mechanism, observations of the composition of the nova ejecta and the rise time of the explosion demonstrate that such mixing occurs. This leads to a series of proton captures and subsequent β -decays, where the heavier nuclei from the white dwarf act as seed nuclei. The result is the synthesis of new

elements, up to the intermediate mass region ($A \sim 40$), that were not present in the original white dwarf. During the explosion, much of the accreted envelope containing the newly synthesized nuclei is ejected into space thereby enriching the interstellar medium.

The results of nova nucleosynthesis depend on whether the nova took place on a CO or ONe white dwarf, with the latter capable of synthesizing heavier elements up to calcium due to a higher peak temperature and the presence of heavier seed nuclei [25]. The focus of this work is constraining the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate in classical novae involving ONe white dwarfs.

1.2.2 The Role of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ Reaction Rate

The $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction acts as a bottleneck for nucleosynthesis beyond $A = 30$ in ONe novae [25]. This is due, in part, to the relatively long β^+ -decay half life of ^{30}P ($t_{1/2}=2.5$ minutes), which is of the same order as the timescale of the TNR. Figure ?? shows the region of the chart of nuclides around ^{30}P , with arrows indicating the reactions expected to play a role in nucleosynthesis in ONe novae. Neutron capture will not contribute significantly to the destruction of ^{30}P due to the low density of neutrons in the accreted, or white dwarf material. The alpha capture reaction $^{30}\text{P}(\alpha,\gamma)^{34}\text{Cl}$ is extremely slow at classical nova temperatures compared to proton capture due to the increased charge of the α particle ($Z=2$) and therefore increased Coulomb barrier. Therefore, once ^{30}P is produced in a classical nova, it will not be destroyed in significant amounts by β^+ -decay, neutron capture, or α capture within the timescale of the TNR, making a proton-capture reaction the only significant mechanism for the destruction of ^{30}P during a nova event. In addition, pathways to higher mass nuclei ($A > 30$) bypassing ^{30}P are strongly inhibited in the classical nova environment. Considering the potential path through ^{29}P via $^{29}\text{P}(p,\gamma)^{30}\text{S}(p,\gamma)^{31}\text{Cl}$, we find that, due to the low proton separation energy of ^{31}Cl (283 keV), the competing photodisintegration reaction $^{31}\text{Cl}(\gamma,p)^{30}\text{S}$ is energetically favorable at the temperatures in question. Therefore, ^{30}S , with a β^+ -decay half life of ~ 1 second, will decay to ^{30}P . An even more proton-rich path is not possible as ^{30}Cl is proton unbound. Proceeding to higher mass along stability via single proton captures followed by β^+ -decay, $^{28}\text{Si}(p,\gamma)^{29}\text{P}(\beta^+)^{29}\text{Si}(p,\gamma)^{30}\text{P}(\beta^+)^{30}\text{Si}(p,\gamma)$ and continuing to higher

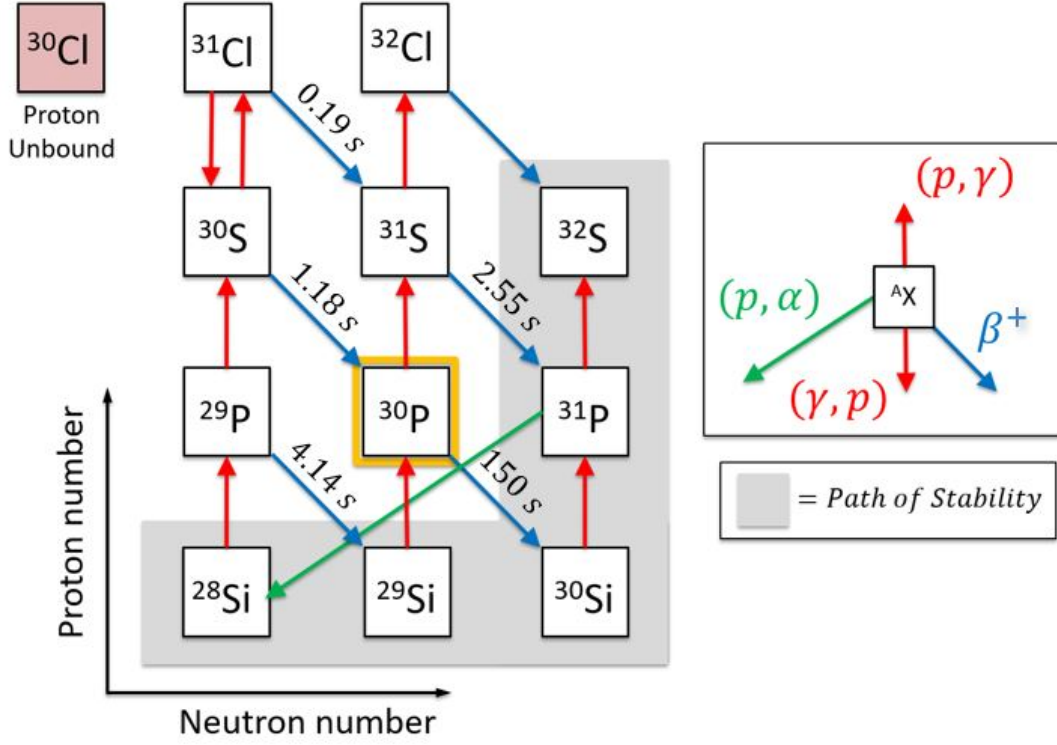


Figure 1.3: Reaction network illustrating some of the possible reactions occurring in classical nova in the region of ^{30}P . The numbers listed on the blue arrows indicating β^+ -decay are the decay half lives.

masses is inhibited by the long β^+ -decay half life of ^{30}P . An alternate scenario could involve ^{30}Si as a seed nucleus and a pathway along stability via proton captures up to ^{32}S , however this requires a large initial abundance of ^{30}Si . There is not expected to be enough ^{30}Si in an ONe white dwarf, or the accreted material for such a pathway to be significant because ^{30}Si is not produced in carbon burning due to the equality of protons and neutrons in ^{12}C . Therefore, the only viable path left for the mass flow through this region to higher mass ($A > 30$) involves the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction followed by either $^{31}\text{S} \beta^+$ -decay or the $^{31}\text{S}(p,\gamma)^{32}\text{Cl}$ reaction.

1.3 Nuclear Thermometers for Novae

In the work by Downen et al.[6] the authors explore the effect of peak nova temperature on the ratios of elemental abundances in the ejecta. The goal of their work was to investigate

the usefulness of “nuclear thermometers” based on observed elemental abundances for determining the peak temperatures of classical novae. A series of one-dimensional hydrodynamic models using the code SHIVA [27] were generated with the reaction rates adopted from STARLIB [28]. The resulting elemental abundances as a function of peak nova temperature are shown in Figure 1.4 All of the models used assumed a mixing of 50% between the accreted material and the underlying white dwarf material prior to the TNR.

In a follow up study, a similar approach was taken to study the degree of mixing prior to nova ignition to develop a “nuclear mixing meter” for classical novae [29]. The results from the nuclear mixing meter study were compared to observations of ONe novae and it was found that the mixing fraction is most likely closer to $\sim 25\%$. Meaning there are a smaller number of heavy seed nuclei present prior to the TNR. Therefore, the final abundance ratios of higher mass nuclei to the nuclei present in the accreted material are reduced.

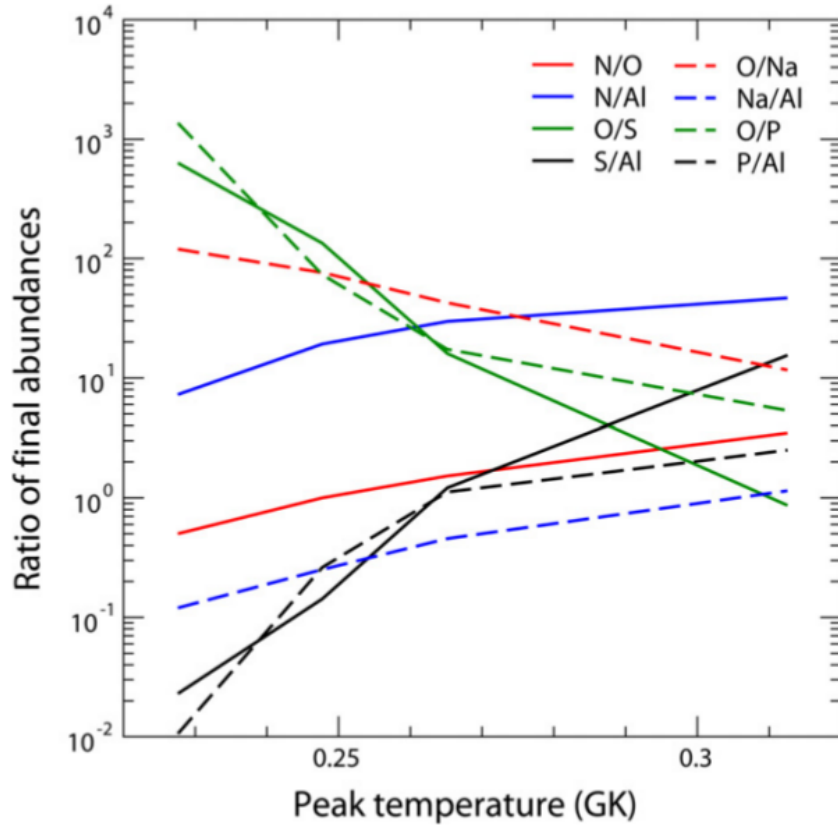


Figure 1.4: Ratios of elemental abundances as function of peak nova temperature, derived from hydrodynamical nova models. Reproduced from Downen, et. al., [6]

The nuclear thermometer study found that several elemental abundance ratios had a strong monotonic dependence on peak temperature and therefore could be useful as thermometers. Due to their variation of several orders of magnitude across the range of expected peak nova temperatures, the most promising elemental abundance ratios were O/S, S/Al, O/P, and P/Al (the green and black curves in Figure 1.4). It was also found that these four ratios are poorly constrained by nuclear data, with the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate contributing the most to the uncertainty [6]. To improve the usefulness of these elemental abundance ratios as nuclear thermometers for novae, it is necessary to further constrain the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction rate at classical novae temperatures.

1.4 Presolar Grains from Novae

Presolar grains are small pieces of solid matter that condensed in the interstellar medium after being ejected from a star. Some of these grains were able to remain intact during the formation of our solar system by becoming lodged in larger pieces of material like planetesimals that remained far enough from the sun to remain unaltered. We can find presolar grains in primitive meteorites, which are large pieces of stony material that have experienced very little alteration since the formation of the solar system and eventually ended up falling to the surface of the Earth. Presolar grains can be isolated and studied by breaking up and dissolving primitive meteorites. The isotopic composition of individual grains can be analyzed, typically via secondary ion mass spectrometry, and used to infer the unique stellar nucleosynthesis event from which they originated [30]. An example of using isotopic ratios to identify the origin of presolar grains is shown in Figure 1.5.

To date a handful of presolar grains have been discovered that could potentially have originated in a classical nova [30]. Presolar grains with a classical nova origin are expected to have a very low $^{12}\text{C}/^{13}\text{C}$ ratio compared to solar values. While their $^{14}\text{N}/^{15}\text{N}$ ratio has been shown to have a wide range from lower than solar to much higher, this ratio is linked to the peak temperature of the event and therefore can help distinguish grains originating in CO novae from those originating in ONe novae [31]. In addition, neon ratios can be an

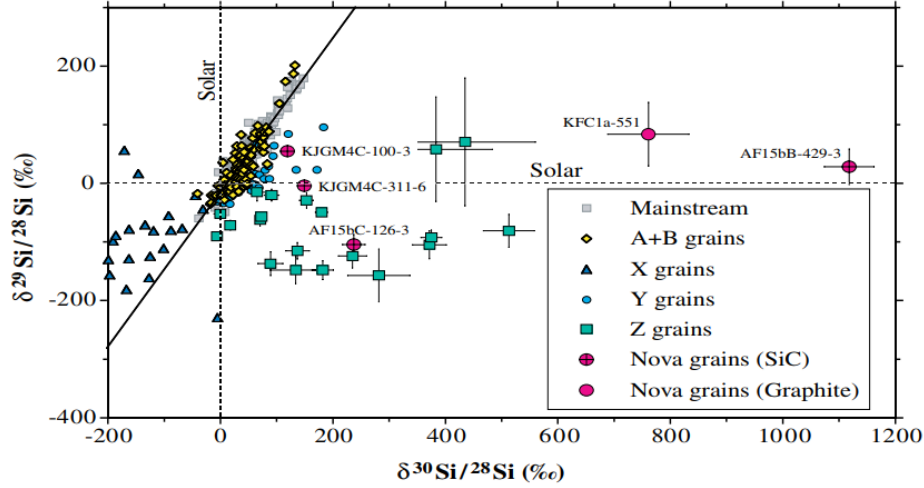


Figure 1.5: Comparison of the $^{30}\text{Si}/^{28}\text{Si}$ ratio of different presolar grains. Grains with a $^{30}\text{Si}/^{28}\text{Si}$ value much larger than solar values point to a nova origin (purple points). Figure reproduced from Jose et. al. [7].

indicator of the type of nova that produced the grain. ONe novae are expected to have ratios of $^{20}\text{Ne}/^{22}\text{Ne}$ that are much higher than solar values, due to neon being dredged up from white dwarf material and mixing with the accreted envelope. However, since neon is a noble gas, it does not easily condense into a grain and therefore is often very scarce in typical samples.

While in CO novae the lack of heavier seed nuclei prevents the synthesis of silicon isotopes, the ratios of $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ are very useful in identifying presolar grains from ONe novae. Models have shown that the $^{30}\text{Si}/^{28}\text{Si}$ ratio increases monotonically with the mass of the white dwarf [30]. Therefore, if the production and destruction of both isotopes are well understood in nova environments, the $^{30}\text{Si}/^{28}\text{Si}$ ratio can be used to measure the mass of the white dwarf involved in the nova that produced the grain. This ratio is particularly sensitive to the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate as ^{30}Si is produced via $^{29}\text{Si}(p, \gamma)^{30}\text{P}(\beta^+)^{30}\text{Si}$ and the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction directly competes with this path. The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate influences the amount of ^{30}P that is allowed to β -decay into ^{30}Si and therefore directly affects the final abundance. Reducing the uncertainty in the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate would increase our ability to extract accurate information about ONe classical novae from silicon isotopic ratios in presolar grains of nova origin.

Chapter 2

Theory and Background

2.1 Measuring The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ Reaction Rate

A logical next step would be to attempt to measure the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate across the relevant astrophysical energy range directly in a laboratory. However, it is currently not feasible to attempt a measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction at astrophysical energies for a number of reasons. As ^{30}P is a short-lived radioactive isotope, it must be created as a radioactive beam to be studied in a reaction experiment. In the US, there are two facilities that have demonstrated the capability of producing a ^{30}P beam at sufficient rates for reaction studies, the National Superconducting Cyclotron Laboratory (NSCL) and the Argonne Tandem Linear Accelerator (ATLAS) facility. The NSCL has produced a ^{30}P beam at 30 MeV/A with an intensity of 1.0×10^6 pps and a purity of $\sim 97\%$ using a fragmentation method [14]. A primary beam of ^{36}Ar was accelerated to 150 MeV/A and used to bombard a thick ^9Be target producing a large range of different nuclei. The ions of interest were then selected using the A1900 fragment separator and delivered to the experimental target [32]. The ATLAS facility can produce a ^{30}P beam at 8 MeV/A with an intensity of $\sim 1.0 \times 10^5$ pps and a purity of $\sim 60\%$ using an in-flight method where a primary beam of stable ^{29}Si is accelerated into a deuterium gas cell and the $^{29}\text{Si}(d, n)^{30}\text{P}$ reaction is used to create the secondary beam of ^{30}P [33].

While these facilities can produce the ^{30}P at a high intensity for some reaction studies, in both cases the beam is delivered at a much higher energy than the relevant astrophysical energies ($E_{CoM} \sim 0.1\text{-}1.0$ MeV) at which the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction would occur in a classical novae. In order to make a direct measurement of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction at the appropriate energies, the ^{30}P beam would have to be stopped and re-accelerated, or degraded, which would lead to a significant loss of intensity. A degraded beam would also suffer a loss in quality, due to energy and angular straggling of the beam in the degrader. Further complicating the measurement, proton capture reactions at astrophysical energies are expected to have very low cross sections due to the need to tunnel through the Coulomb barrier [15]. Combining the low beam rates and the low cross section would make the time required to complete a direct measurement of the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction, at astrophysical energies, prohibitively long for a multi-user facility where beam time is in high demand.

For all of the reasons listed above, it is currently impractical to measure the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate directly. However, the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate can be calculated. The calculation of the reaction rate requires some nuclear structure information about the nuclei involved. Different indirect approaches can be employed to obtain the required nuclear structure information.

2.2 Calculating The $^{30}\text{P}(p,\gamma)^{31}\text{S}$ Reaction Rate

2.2.1 The Gamow Window

To understand which states are important in astrophysical environments, it is useful to look at the Gamow window, as it provides an estimate of the range of energies for which a reaction is likely to occur for a given temperature. The Gamow window arises from a convolution of the velocity distribution of particles in a stellar environment and the probability for the nuclei to penetrate the Coulomb barrier. If we consider the stellar material to be an ideal gas, the velocity distribution of particles is described by the Maxwell-Boltzmann distribution. The tail of the Maxwell-Boltzmann distribution decreases exponentially with energy. The velocity distribution can be written as an energy distribution in the following way [34]:

Table 2.1: Gamow window for the $^{30}\text{P}(\text{p},\gamma)^{31}\text{S}$ reaction

Temperature (GK)	E_0 (keV)	Δ (keV)	$E_0 - \Delta/2$ (keV)	$E_0 + \Delta/2$ (keV)
0.1	158	85	116	201
0.4	399	271	263	534

$$\psi(E) = 2\sqrt{\frac{E}{\pi}} \left(\frac{1}{kT} \right)^{3/2} e^{-\frac{E}{kT}} \quad (2.1)$$

Where T is the temperature and k is the Boltzmann constant. The probability of penetrating the Coulomb barrier increases with energy and is given by,

$$P \propto e^{-b/\sqrt{E}} \quad (2.2)$$

where b is given by,

$$b = \frac{\sqrt{2\mu}}{\hbar} \pi e^2 Z_1 Z_2. \quad (2.3)$$

In this expression, μ is the reduced mass of the two nuclei involved, Z_1 and Z_2 are their atomic numbers, $\hbar$ is the reduced Planck constant, and e is the electron charge.

Folding the two of these together results in a strongly peaked function that can be reasonably approximated as a Gaussian. The standard parameterization of the Gaussian approximation of the Gamow window is described by the following equations for the centroid (E_0) and full width at half of the peak (Δ), respectively [35].

$$E_0 = 0.12204(\mu_A Z_1^2 Z_2^2 T_9^2)^{1/3} \text{MeV} \quad (2.4)$$

$$\Delta = 0.23682(\mu_A Z_1^2 Z_2^2 T_9^5)^{1/6} \text{MeV} \quad (2.5)$$

where μ_A is the reduced mass number,

$$\mu_A = \frac{A_1 A_2}{A_1 + A_2}. \quad (2.6)$$

Taking into account the width of the window, at either end of the temperature range, we find that the region of interest will be $E_r = 116 - 534$ keV. While this range of energy

is informative, resonance states outside this range can still contribute significantly to the reaction rate depending on their resonance strength.

2.2.2 Statistical Method for Calculating Cross Sections

The calculation of a reaction rate requires knowledge of the cross section as a function of energy for the reaction of interest. The cross section for a nuclear reaction is a measure of the probability for the reaction to occur and is expressed in units of area [36]. An early attempt to calculate the astrophysical $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate was made using the Hauser-Feshbach (HF) approach [37]. The HF approach is a method for calculating cross sections of nuclear reactions under the assumption that a compound nucleus is formed and that the nuclear level density in the relevant excitation energy range of the compound nucleus is sufficiently high that the individual levels can be modeled as a continuum and therefore treated statistically [38]. In many cases, this can be a reasonable assumption and the HF method will generate fairly accurate cross sections. Rauscher et al estimate the astrophysical reaction rates they have calculated using the HF method to be accurate within a factor of 1.5-2 [37]. However, when the assumption of a high nuclear level density is not valid, this uncertainty will be larger and a different method for calculating the cross section is desired.

In the case of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction, the level density is not sufficiently high to be modeled as a continuum and therefore the HF approach will have large uncertainties. In this case, the cross section is best calculated by considering the contributions of the individual resonances. However, without the necessary data about the resonant states involved in the reaction, this is not possible. As more information about the resonant states has become available, calculations of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate have been updated, but there is currently poor agreement between different published results (see Fig 2.3). The situation would be improved with the inclusion of new data, as well as the reduction of uncertainties in the already measured quantities. Therefore, additional experiments with the goal of obtaining high-precision information about the resonant states involved in the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction are required to improve the calculations of the reaction rate and thereby improve models of classical nova.

2.2.3 Thermonuclear Reaction Rates for Isolated Resonances

The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction at classical nova temperatures is expected to proceed via narrow and isolated resonances. A narrow resonance is defined as having a width (Γ) much less than the resonance energy. An isolated resonance is defined as having a width much less than the spacing of nearby levels. The reaction cross section is strongly peaked at the energy of a resonance state, as shown in Figure 2.1. The structure of ^{31}S is known well enough to make the assumption that the states in ^{31}S involved in the proton capture on ^{30}P , inside the Gamow window at typical nova temperatures, meet both of these criteria. Therefore it is appropriate to use resonant reaction theory to calculate the cross section of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction at the astrophysically relevant energies.

The resonant reaction rate per particle pair is given by the following equation [39],

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \sum_r (\omega\gamma)_r e^{-E_r/kT} \quad (2.7)$$

where E_r is the resonance energy and μ is the reduced mass. The sum over r is a sum over the resonances in the compound nuclear system. The factor $\omega\gamma$ is known as the resonance strength and for the specific case of a proton-capture reaction is given by,

$$\omega\gamma = \frac{(2J_r + 1)}{(2J_p + 1)(2J_i + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}. \quad (2.8)$$

The Γ_p and Γ_γ factors are known as the partial widths of the resonance and Γ is the total width and is related to the partial widths by, $\Gamma = \Gamma_p + \Gamma_\gamma$.

From these two equations, it is apparent that the calculation of a resonant reaction rate as a function of temperature requires the following input:

- 1.) The resonance energy, E_r
- 2.) The angular momentum of the initial state and resonance state, J_r
- 3.) The proton partial width of the resonance state, Γ_p and
- 4.) The γ -ray partial width of the resonance state, Γ_γ .

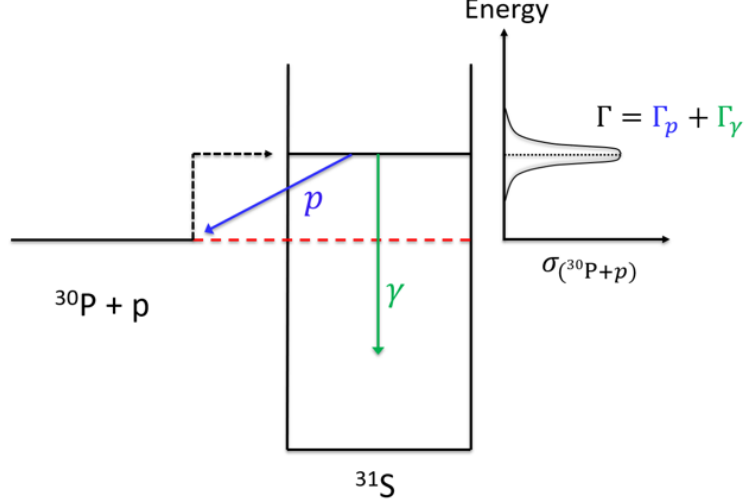


Figure 2.1: Schematic for a resonant proton capture reaction $^{30}\text{P}(p, \gamma)^{31}\text{S}$. The rotated plot on the right shows the cross section for the reaction as function of energy. The cross section is strongly peaked at the resonance energy and the full width half maximum of the peak is resonance width Γ .

To calculate the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate for all resonances in the energy range in question, these nuclear data must be obtained by an indirect method such as the $^{32}\text{S}(p, d)^{31}\text{S}^*$ reaction. While the reaction rate also depends on J_i , the angular momentum of the initial state, at classical novae temperatures this is always the angular momentum of the ^{30}P ground state, $J_i=1^+$. The first excited state of ^{30}P is 677.01(3) keV and classical novae temperatures are not sufficiently high to produce a significant fraction of excited ^{30}P in thermal equilibrium.

2.3 Indirect Approach : The $^{32}\text{S}(p, d)^{31}\text{S}^*$ Reaction

The transfer reaction $^{32}\text{S}(p, d)^{31}\text{S}^*$ was chosen because it can populate many of the same proton unbound levels through which the resonant proton capture reaction, $^{30}\text{P}(p, \gamma)^{31}\text{S}$, proceeds. An assumption fundamental to this approach is that the decay of the nuclear state, $^{31}\text{S}^*$, is independent of the way in which it was formed [36]. If this is true, the branching ratios of the decays of the excited states in ^{31}S produced in the $^{32}\text{S}(p, d)^{31}\text{S}^*$ reaction will be the same when these states are populated via proton capture on ^{30}P in a classical nova explosion.

In order to populate the states of interest, the beam must be of sufficient energy to overcome the threshold for initiating the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction, which is 12.82 MeV, and have enough energy remaining to excite the nucleus to states with excitation energies above the proton separation energy ($S_p = 6.1309(4)$ MeV [1]), through which the resonant proton capture at classical nova temperatures will proceed. The proton separation energy is the energy required to remove a proton from the nucleus and therefore states with excitation energies above the proton separation energy are proton unbound. The threshold for initiating an endothermic reaction is known as the Q-value and will be discussed in Chapter 4. Fig 2.2 shows a diagram depicting the position of states in ^{31}S in relation to the ^{30}P ground state and examples of different decay modes are shown by the different colored arrows. The resonance energy of these states is the difference of the excitation energy in ^{31}S and the proton separation energy. In general, any state above the proton threshold will have a probability of decaying through γ -ray emission to the ^{31}S ground state, or proton emission to ^{30}P . However, as the resonance energy increases, it is expected that proton decay will be the dominant form of de-excitation, while low-lying resonances close to threshold energy are expected to have significant γ -ray de-excitation branches. This effect is primarily due to the Coulomb barrier. Protons excited to unbound states can still be below the Coulomb barrier and therefore will have to tunnel through the barrier to leave the nucleus. As the energy of the state increases, the probability for a proton to tunnel through the Coulomb barrier increases, leading to an increased likelihood that the state decays via proton emission. It is important to note that if the resonance energy is sufficiently high, it is possible for there to be additional proton decay branches to excited states in ^{30}P , which will then de-excite via γ -ray emission.

2.4 Previous Efforts to Constrain the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ Reaction Rate

Since the identification of the importance of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate in classical novae involving ONe white dwarfs [25], many experimental efforts have been carried out

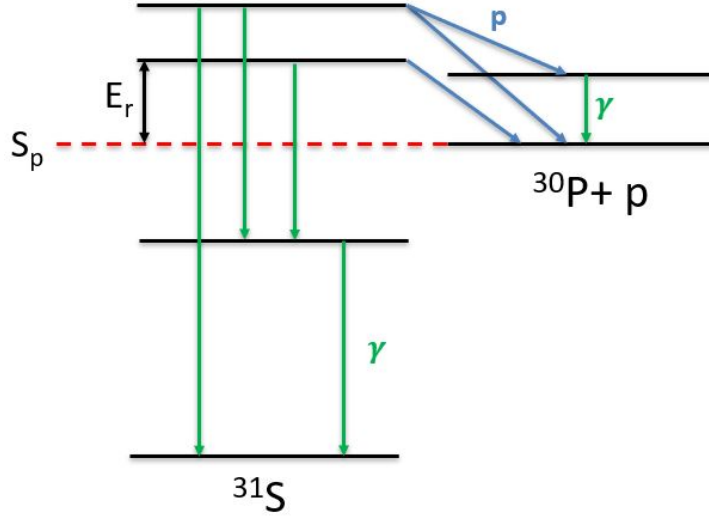


Figure 2.2: Schematic level scheme showing possible decay modes of states above the proton separation energy in ^{31}S . Green arrows denote γ -ray emission while the blue arrow denote proton emission.

with a goal of constraining the reaction rate at the relevant temperatures. These experiments involved indirect methods of obtaining information about the excited states above the proton threshold in ^{31}S (and its mirror ^{31}P) and include β -decay studies [40, 41] and various single-nucleon transfer [14, 13, 42], charge-exchange [9, 43, 4], and fusion evaporation reactions [8, 10].

A summary of the currently available data about the excitation energies and spin-parities of the astrophysically important states in ^{31}S is shown in Table 2.2. The most recent evaluation occurred in February 2013 [1] and these results are listed in the first column. The next three columns list results from experiments performed since the evaluation. It is important to note that the spin-parity assignments of many states remain unconfirmed (as denoted by values in parentheses). In addition, there are some disagreements between reported J^π values, for example the state at $E_x = 6394$ keV has been reported as having $J^\pi = 5/2^+$ and $J^\pi = 11/2^+$. Another important point is the discovery of a new state in the most recent experiment [41] that has not been observed by any other measurement, and therefore still requires confirmation.

2.4.1 Detection of Proton Decays

There have been at least two previous experiments that were sensitive to proton decays of the states in ^{31}S above the proton threshold [40, 4]. Both of these experiments were successful in observing decay protons. However, they were unable to measure the protons from the lower energy resonances $E_r \lesssim 600$ keV ($E_p \lesssim 600$ keV) due to difficulties with electronic noise in their experimental setup. The measurement by Kankainen et al. [40] used ^{31}Cl β -decay to populate levels in ^{31}S and observe the subsequent proton decay. This method is effective for measuring branching ratios but can not offer any information about the angular momentum of the decay.

In the measurement by Wrede et al. [4], the $^{31}\text{P}(^3\text{He}, t)^{31}\text{S}$ reaction was used to populate levels in ^{31}S and observe the subsequent proton decay. With this method, angular correlations between the reaction product and the decay proton can be measured and used to constrain the angular momentum of the decay. However, the setup for Wrede’s measurement was only sensitive to a small range of angles between the reaction product and the decay proton and therefore had limited information about the angular momentum of the decay. The experiment described here sampled a large angular range ($90^\circ - 180^\circ$) between the reaction product and the decay proton, which provided more information about the angular momentum of the decay. The sensitivity to a larger angular range required the development of new analysis techniques in the detection of a decay proton following a nuclear reaction. The development of these analysis techniques is an important part of this work and will be discussed in Chapter 4.

2.4.2 Evaluation of the Reaction Rate

A comparison of multiple calculations of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate is shown in Figure 2.3(b). The Figure is reproduced from Doherty et al. [8], where the authors have plotted their result (solid line) along with the results of Parikh et al. [9] (dashed lines) and Jenkins et al. [10] (dotted line). The reaction rates are presented as a ratio to the statistical method result of Rauscher et al. [37]. These separate calculations differ by up to two orders of magnitude

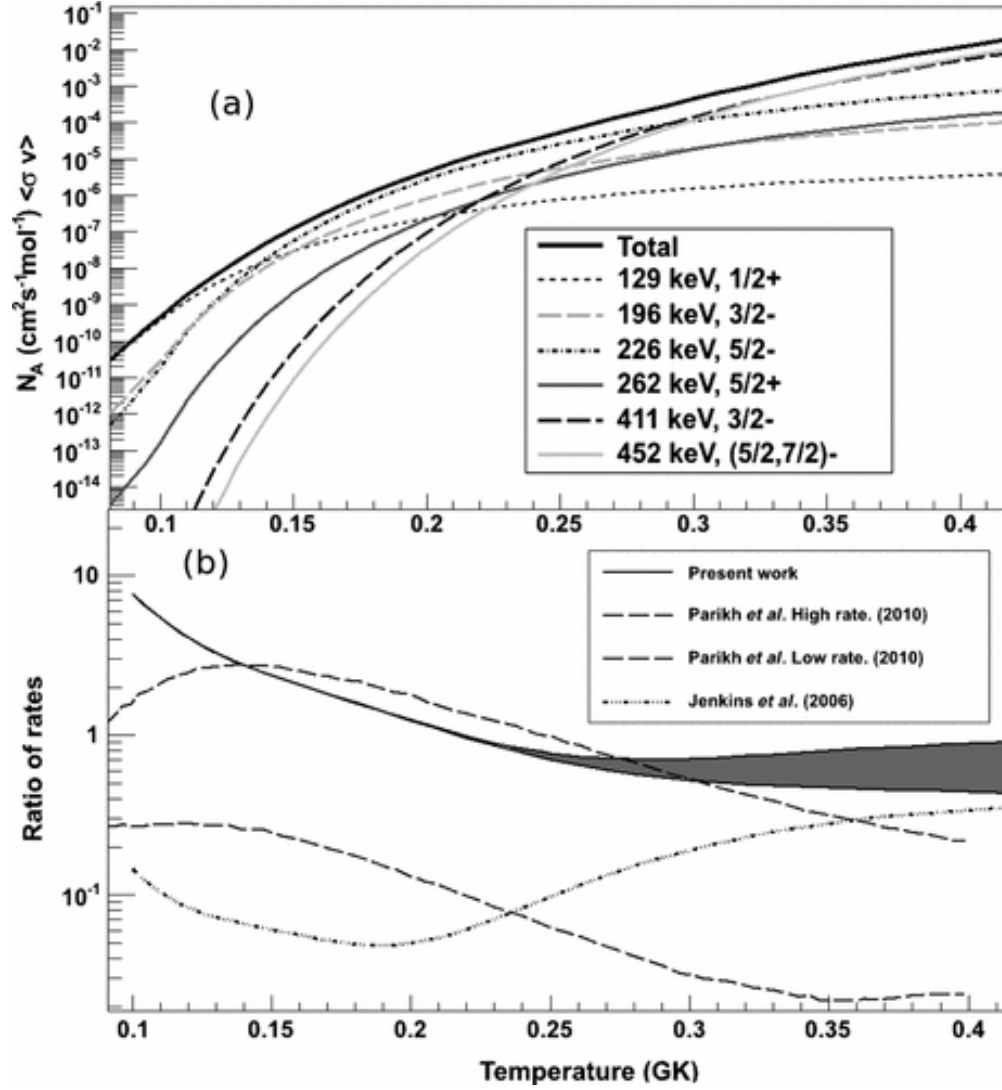


Figure 2.3: Figure reproduced from Doherty et al. [8]. (a) The authors calculation of the contributions of individual resonant states to the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate. (b) Comparison of multiple reaction rate calculations presented as a ratio to the statistical method result. The two dashed lines are from a measurement by Parikh et al. [9] where the difference in the high and low rate is nearly an order of magnitude and can be attributed to uncertainties in the J^π of states in ^{31}S as well as unknown proton spectroscopic factors that went into the calculation of Γ_p . The dotted line is the results of measurement by Jenkins et al. [10]. The solid line is the work of Doherty et al., where the shaded region represents the uncertainty due to the ambiguous spin-parity assignment of the 452 keV resonance.

due to differences in the nuclear data used to calculate reaction rate. For example, the difference in the rate shown by the two dashed lines representing the “high” and “low” rate of Parikh et al. are attributed to uncertainties in J^π of states in ^{31}S as well as assumptions made about the spectroscopic factors, which were used in the calculation of Γ_p . The large disagreement in the reaction rates calculated by the different authors demonstrates the need for more measurements of the astrophysically relevant states in ^{31}S to reduce the uncertainty in the nuclear data used as input.

Table 2.2: Nuclear data for astrophysically relevant states in ^{31}S from recent experiments, with the exception of the first column, which is reproduced from the most recent Evaluated Nuclear Structure Data File (ENSDF) for ^{31}S (evaluated February 2013) [1].

ENSDF [1]		$^{32}\text{S}(\text{d,t})$ [42] [a]		$^{28}\text{Si}(\alpha,\text{n}\gamma)$ [44] [b]		^{31}Cl ε decay [41] [c]	
E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)	J^π
6138.6(6)	(7/2 ⁺)			6138.3(21)	(3/2,7/2) ⁺		
6160.0(6)	(5/2 ⁻ ,7/2 ⁺)			6158.5(5)	7/2 ⁺		
6255.3(5)	1/2 ⁺					6255.0(6)	1/2 ⁺
6280.60(16)	3/2 ⁺					6279.0(6)	3/2 ⁺
6327.0(5)	(3/2)			6327.0(5)	3/2 ⁻		
6357.32(22)	(5/2 ⁻)	6356(2)	5/2 ⁻	6357.3(2)	5/2 ⁻		
6376.7(3)	(9/2 ⁻)			6376.9(4)	9/2 ⁻		
						6390.2(7)	3/2 ⁺
6392.43(22)	(5/2 ⁺)			6392.5(2)	5/2 ⁺		
6394.36(22)	(11/2 ⁺)	6394(1)	5/2 ⁺	6394.2(2)	11/2 ⁺		
6401(3)		6402(2)	7/2 ⁽⁻⁾				
6420.7(6)	(1/2 ⁺ ,3/2 ⁺ ,5/2 ⁺)						
6541.9(4)	(3/2 ⁻)	6543(2)	3/2 ⁻	6541.9(4)	3/2 ⁻		
6582.9(20)	(7/2)	6584(1)	(5/2,7/2) ⁻	6583.1(20)	(5/2,7/2) ⁻		
6636.3(3)	(9/2 ⁻)			6636.1(7)	9/2 ⁻		
6720(2)	(5/2)	6720(1)					
6749(2)	3/2 ⁺	6749(2)					
6796(25)							
6833.2(3)	(11/2 ⁻)						
6836(2)							
6848(9)							
6872(2)	(11/2)	6869(2)					
6937(2)	(1/2 ⁺ ,3/2 ⁺ ,5/2 ⁺)	6935(2)					
6961(3)		6958(2)					
6975(3)	1/2 ⁺	6971(2)					

^a Excitation energies measured using a magnetic spectrometer. Spin-parity assignments are based on mirror symmetry arguments for levels in ^{31}S and ^{31}P .

^b Excitation energies measured via γ -ray spectroscopy. Spin-parity assignments are based on γ -ray angular distributions.

^c Excitation energies measured via γ -ray spectroscopy. For the newly observed state (6390.2(7) keV) the spin-parity assignment was made based on observation of isospin mixing with isobaric analog state (IAS).

Chapter 3

Experiment

3.1 Texas A&M Cyclotron Institute

The experiment was performed at the Texas A&M Cyclotron Institute. The K150 cyclotron was used to accelerate a proton beam to 33.05 ± 0.05 MeV. The beam current ranged from 0.5-1.8 nA throughout the experiment, where the beam current delivered to target could be adjusted using a focusing solenoid on the ion source extraction beam line. Depending on the thickness of the target being used, the beam current was adjusted such that the data acquisition system maintained a livetime of $\sim 80\%$.

3.2 The Hyperion Array

The Hyperion Array, shown in Figure 3.2, is a combined charged-particle and high efficiency γ -ray detector array built by Lawrence Livermore National Laboratory and based at Texas A&M University [11]. In its full configuration Hyperion consists of 14 Compton-suppressed high-purity germanium (HPGe) clover detectors. During this experiment only 12 HPGe clover detectors were available for the setup, and of the 12, only 8 were functioning properly.

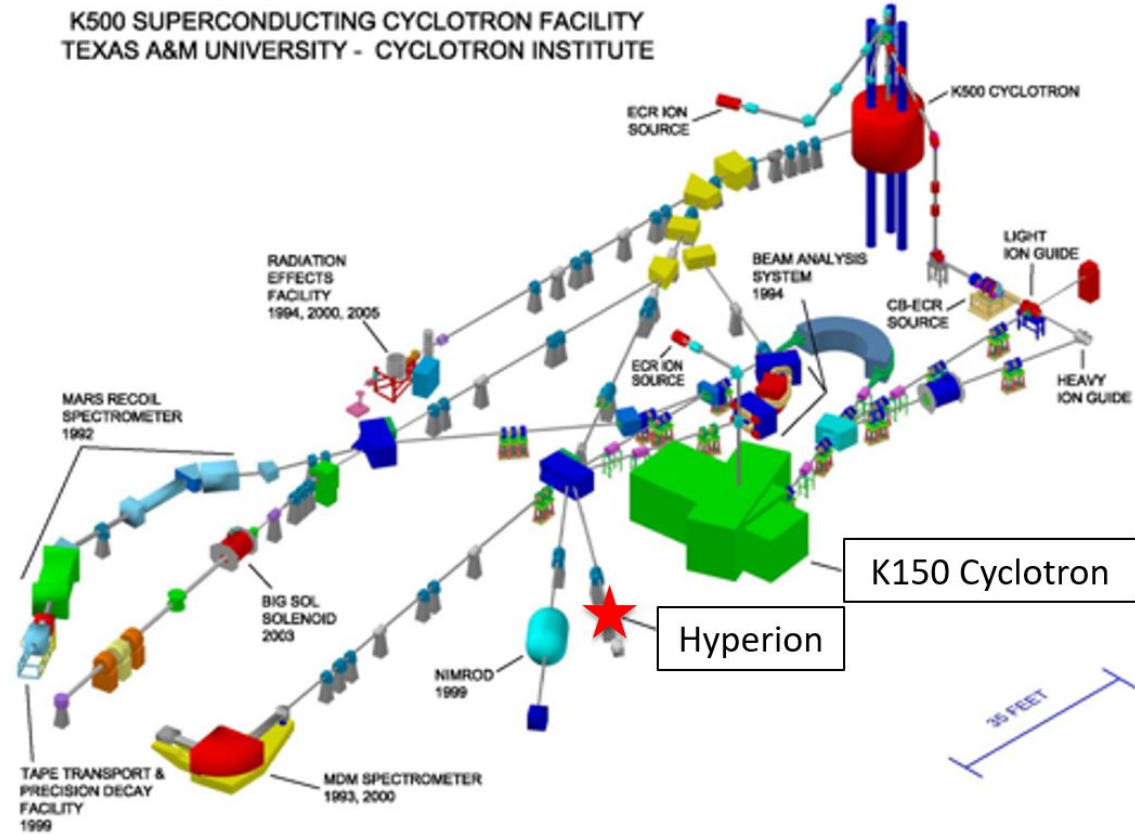


Figure 3.1: Layout of the Texas A&M Cyclotron Institute. The red star denotes the location of the Hyperion array.

3.2.1 Gamma-Ray Detection

HPGe clover detectors consist of four separate germanium crystals (leaves) each having their own electrical contact and therefore individual signal readout. The crystals are assembled in a configuration resembling a 4-leaf clover, hence the terms clover and leaf are used for the entire detector and individual crystals respectively. The clovers in the Hyperion array are positioned at a distance of 21 cm from the target position.

Each clover was mounted inside a Bismuth germanate (BGO) shield. BGO is a scintillator with very high efficiency for γ -ray detection, but comparatively poor energy resolution. Each BGO shield is comprised of a BGO crystal coupled to 16 photo-multiplier tubes (PMTs). The signals from the 16 PMTs were chained together such that there was one signal readout per BGO shield. The BGO shields were used as a veto detector in the offline analysis,

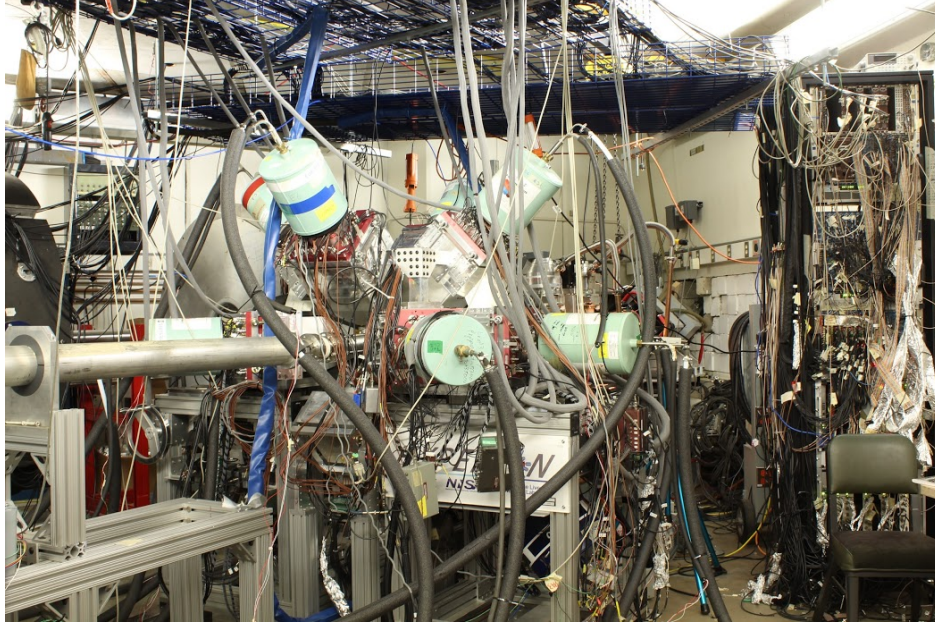


Figure 3.2: The Hyperion Array in the closed position. The data acquisition electronics rack can be seen on the right side of the image.

meaning events in the HPGe detector that come in coincidence with an event in the BGO shield are rejected in the offline data analysis. (See Fig 3.3) This provided suppression of the Compton-scattered γ -rays which deposited only a fraction of their energy inside the active volume of the clover.

The HPGe clover detectors were used in “add-back” mode, meaning that in the case when multiple leaves in a single clover record a signal in a given event, the energies recorded in the individual leaves are summed together to reconstruct the full energy of the incident γ -ray. The implementation of add-back greatly increases the efficiency for the detection of high energy γ -rays. This is due to the fact that high energy γ -rays are less likely to deposit their full energy in a single leaf and tend to Compton scatter and deposit energy in two or more leaves of a given clover. The states in ^{31}S of interest for this measurement have possible γ -ray decay branches involving γ -rays in excess of 6 MeV, the detection efficiency of which is increased with the use of add-back.

The γ -rays are emitted from a moving source, the recoiling nucleus, and therefore their energies are Doppler shifted when observed by the detectors in the laboratory. The details

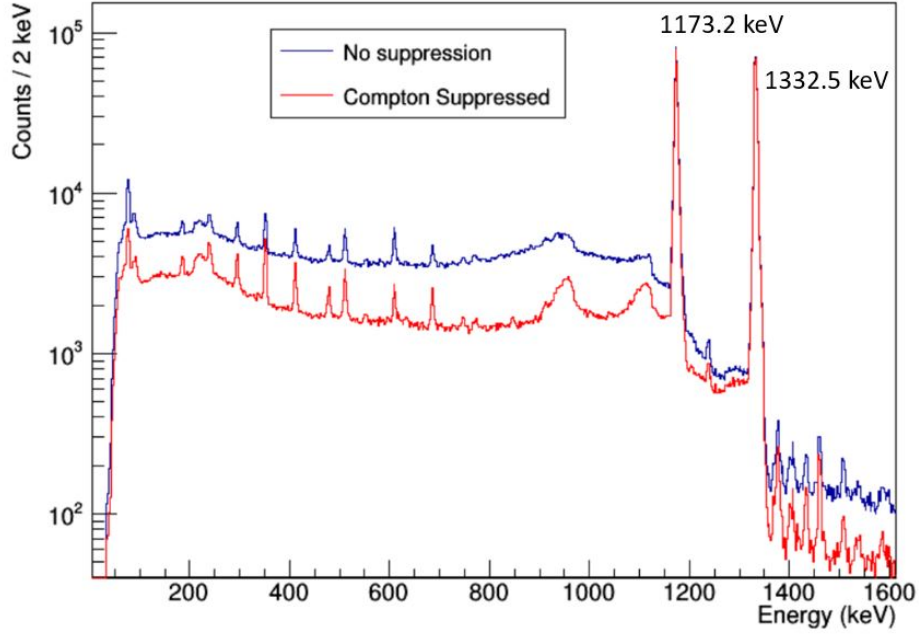


Figure 3.3: Comparison of a ^{60}Co decay spectrum recorded with the Hyperion array using Compton suppression (red) and with no suppression (blue). The spectra were recorded using the entire array with the clovers in “add-back” mode. The contribution from the low energy continuum is reduced while the ^{60}Co photo-peaks (1173.2 keV and 1332.5 keV) are unchanged. (The smaller peaks at lower energies are due to room background.)

of the Doppler correction are discussed further in Chapter 4. An important input to the Doppler correction is the angle between the recoil nucleus and the γ -ray. The segmentation of the HPGe clover detectors into the separate leaves provides better angular resolution for the detection of γ -rays and therefore increases the quality of the Doppler correction.

The energy deposited by a photon in a Compton scattering event is proportional to its initial energy and also depends on the angle of the scatter. A γ -ray entering the detector has its maximum energy before its first Compton scatter, therefore it is most likely to deposit the largest amount of energy at its first interaction point. In the case of a γ -ray event where two or more leaves record an energy, the γ -ray is assumed to have hit the leaf in which the most energy was deposited first and the angle of this leaf is used for the Doppler correction.

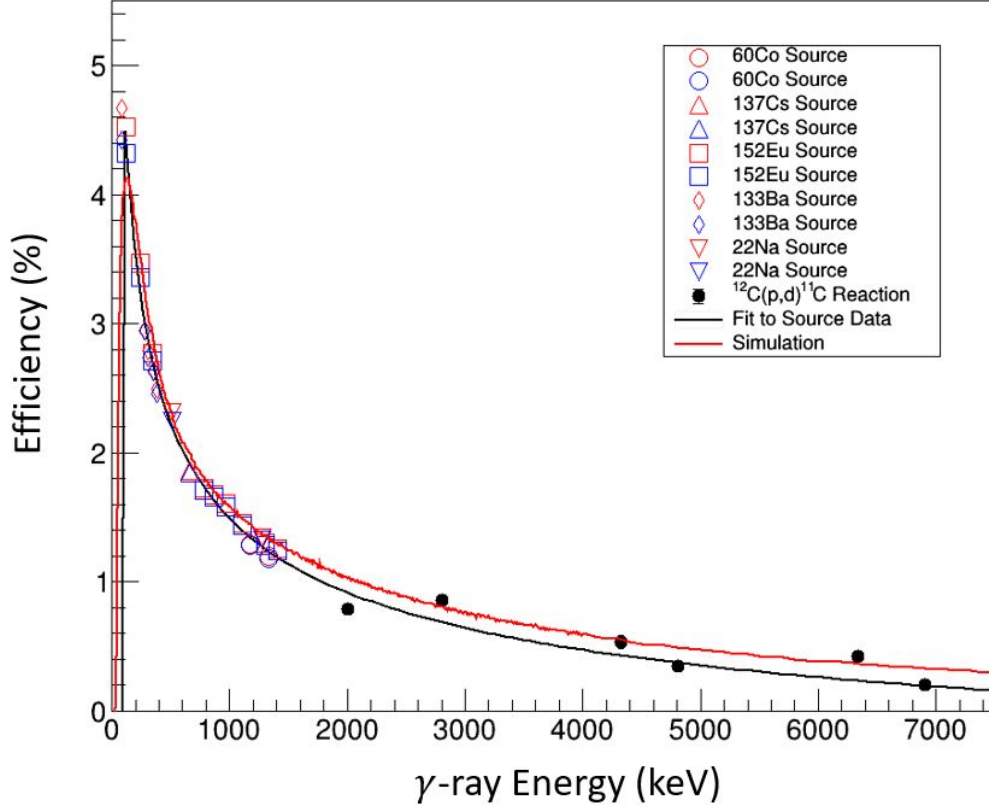


Figure 3.4: Measurements of the efficiency of the HPGe clovers of the Hyperion Array. The different shape open points are measurements taken with radioactive sources placed at the target position. The red points were taken before the experiment and the blue data points were taken after the experiment. The solid black line is a fit to both source data sets. The solid black circles are efficiency measurements from the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction, these points are not included in the fit. The solid red curve is the data from a Monte Carlo simulation of the Hyperion array performed by Hughes et al [11]. The simulation was performed with the full 14 HPGe clovers that are able to be mounted in the Hyperion Array. During this experiment only 8 clovers were working and two of those clovers were missing two leaves each, therefore the simulation results have been scaled down by a factor of 0.5 to match the experimental results.

Gamma-Ray Detection Efficiency

The efficiency of the HPGe clovers in the Hyperion array were characterized using a number of radioactive sources placed at the target position. A set of measurements was performed before and after the experiment to check for consistency. The results from the source measurements can be found in Figure 3.4. The different shape points correspond to different sources and the color indicates whether the run was taken before the experiment or after, with blue indicating after and red before. The black curve is a fit to the source data using the function shown in Equation 3.1.

$$\varepsilon(E_\gamma) = c_0 E_\gamma^{-c_1} - c_2 e^{-c_3 E_\gamma} + c_4 \quad (3.1)$$

To check the accuracy of the fit to the source data when extrapolated to the γ -ray energies expected in the experiment and to verify its validity in a reaction setting, the γ -ray de-excitations following the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction were used to measure the efficiency up to ~ 7.0 MeV. In addition, the measured efficiency was compared to the results of a Monte Carlo simulation (solid red curve in Figure 3.4) performed by Hughes et al [11]. The simulation was performed with the full 14 HPGe clovers that are able to be mounted in the Hyperion Array. During this experiment only 8 clovers were working and two of those clovers were missing two leaves each, therefore the simulation results have been scaled down by a factor of 0.5 to match the experimental setup.

3.2.2 Particle Detection

The Hyperion Array [11] is designed to use up to four Micron Semiconductor S2 silicon detectors for charged particle detection (shown in Fig 3.5). The S2 detectors consist of 48 concentric rings on the front side and 16 wedge shaped sectors on the back side. For this setup, the rings and sectors are grouped into pairs of two so there are only 24 readout channels for the front and 8 readout channels for the back side for a total of 32 signal channels per detector.

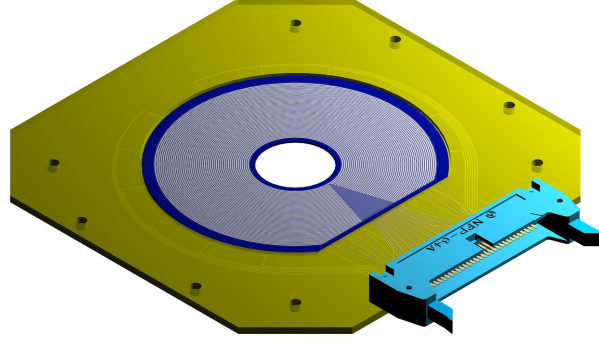


Figure 3.5: Micron Semiconductor Ltd. S2 Silicon detector [12] (front side)

For this experiment, three S2 detectors were used. There were two silicon detectors downstream in a ΔE -E telescope configuration where the ΔE and E detectors were $150\ \mu\text{m}$ and $1500\ \mu\text{m}$ thick respectively. The downstream telescope was used for particle identification of direct reaction products and elastically scattered beam particles. A δ -electron shield of $16\ \mu\text{m}$ of aluminized mylar was mounted in front of the silicon telescope. The third silicon detector had a thickness of $500\ \mu\text{m}$, and was placed upstream for the detection of decay protons. The silicon telescope was mounted 28 mm from the target position and the upstream silicon detector was mounted 35 mm from the target. Fig 3.6 and Fig 3.7 show the silicon telescope and upstream detector respectively mounted inside the scattering chamber in the position used for the experiment.

Due to the fact that this reaction was measured in normal kinematics, there was very little cross section for direct reaction products at backward angles. Therefore decay protons were more easily detected in the upstream detector were the rate from reaction products was reduced. Decay protons were identified as events in the upstream detector, which were detected in coincidence with a deuteron in the telescope.

Silicon Telescope

Particle identification (PID) was achieved using a ΔE -E silicon telescope. A silicon telescope consists of two or more silicon detectors assembled in a stack. The front detector

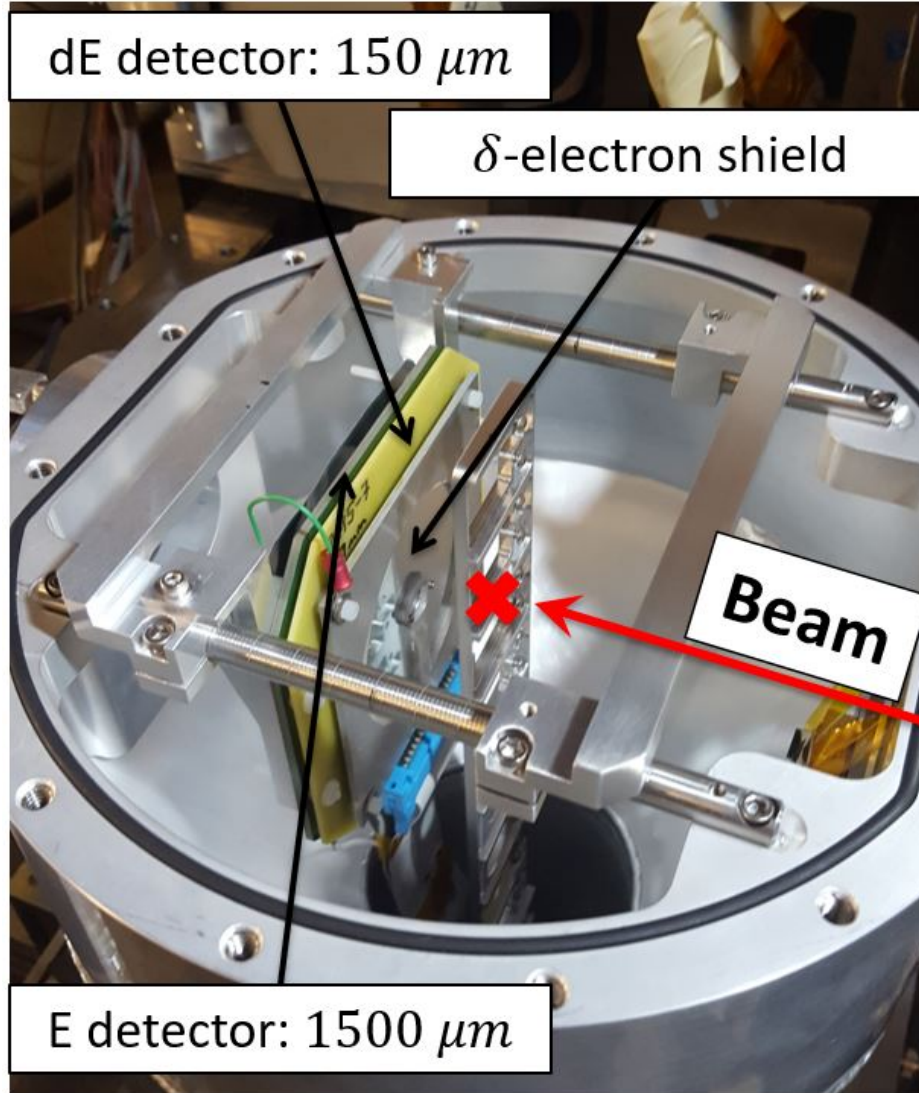


Figure 3.6: The downstream silicon telescope with the δ -electron shield in place. The red arrows show the direction of the beam and the red crosses show the target position.

is typically thin and is known as the ΔE and the back detector(s) is known as the E, and is typically much thicker. In the ideal scenario, an incoming charged particle will pass through the ΔE detector, depositing some portion of its energy, and come to a stop in the E detector depositing its remaining energy. There is a correlation between the energy deposited in the ΔE detector and E detector. This correlation depends on the nuclear charge (Z), mass, and total energy of the incoming charged-particle. A particle identification plot is made by plotting the energy deposited in the ΔE detector versus the total energy ($\Delta E + E$) for particles incident on the silicon telescope. A typical PID plot from a single run can be found

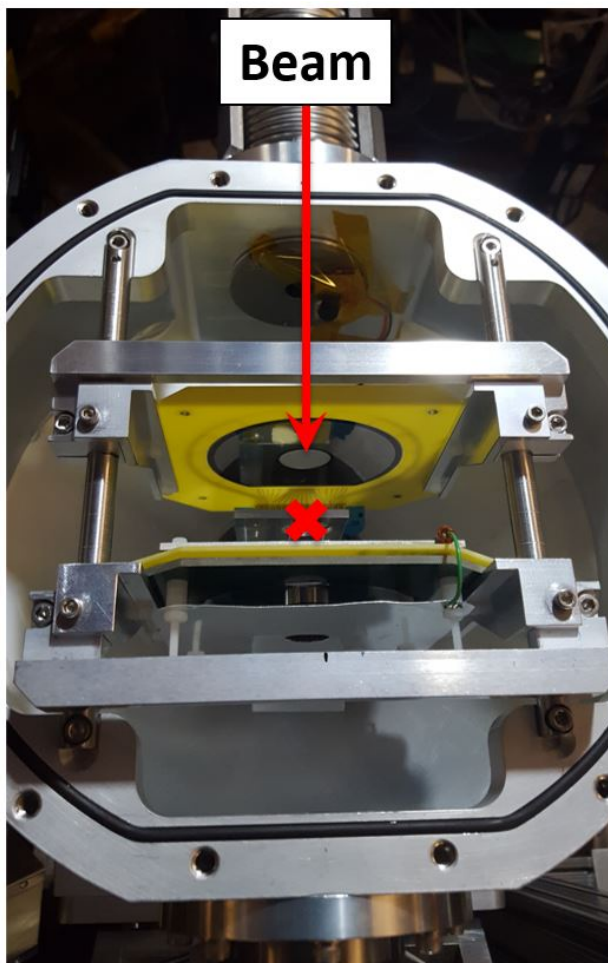


Figure 3.7: The upstream silicon detector. The red arrows show the direction of the beam and the red cross shows the target position.

in Fig 3.8. Here, it is possible to distinguish protons, deuterons, tritons, ^3He , and ^4He . For this experiment a 2D gate was drawn around the deuterons in the PID plot to select only events in which a (p, d) reaction has taken place.

3.3 Data Acquisition and Electronics

The data acquisition (DAQ) consisted of analog electronics. The trigger for the DAQ was a coincidence in the ΔE and E detectors. The signals from the silicon detectors were connected to feed-through boards, which brought the signal out of the vacuum chamber. Pre-amplifiers were mounted on the feed-through boards on the outside of the chamber.

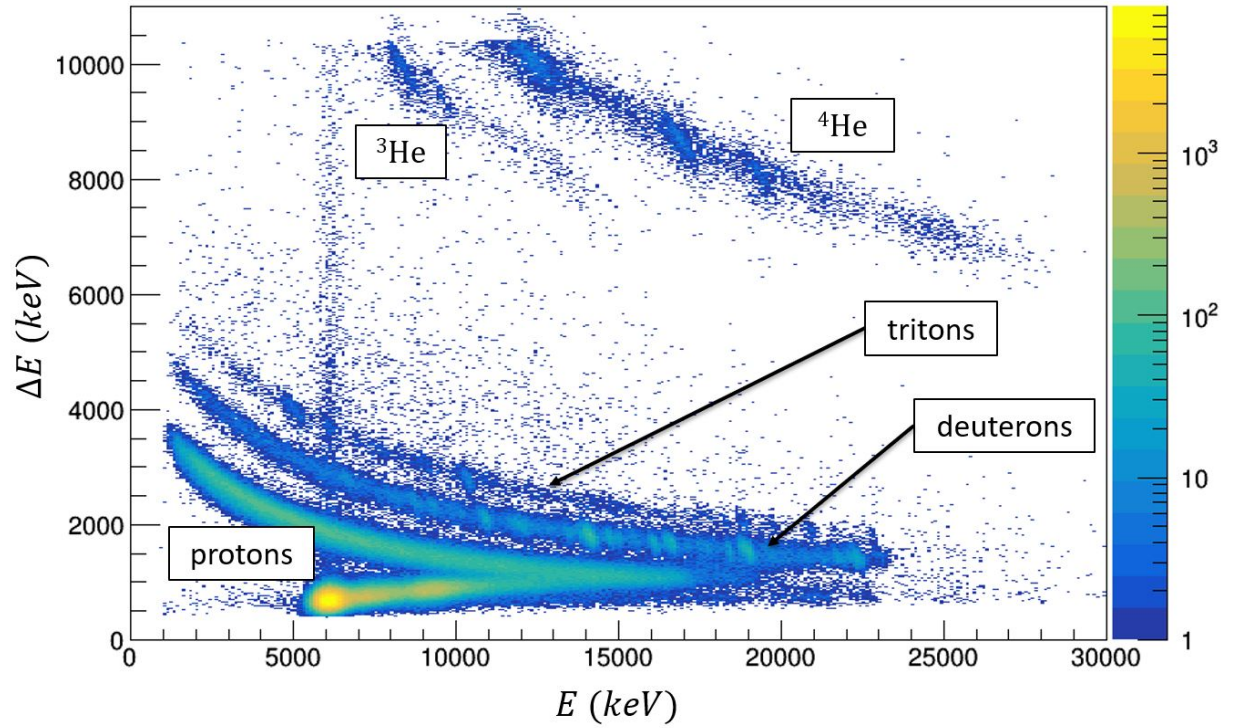


Figure 3.8: Particle identification plot. The energy deposited in the ΔE detector is plotted against the total energy ($\Delta E + E$). Different isotopes are separated by both their charge and mass, producing curved loci. Notice that the band for protons bends around back to lower energies. This bend is due to the fact that high energy protons scattered from the target do not fully stop in the silicon telescope (punch-through) and therefore do not deposit their full energy. The intense bright spot at the end of this bend corresponds to elastically scattered protons that punch-through ΔE and E detectors.

The pre-amplified signals were then sent to Caen N568B shaping amplifiers. The shaped signals were fed to Mesytec MADC32 peak-sensing Analog to Digital Converters (ADCs) [45]. Signals coming from HPGe detectors were pre-amplified on board the detector and then sent to Mesytec MSCF-16 shaping amplifiers [46]. The MSCF-16 shaping amplifiers have a fast output used for timing, the signals from this output were sent to a Caen V1190A Time to Digital Converter (TDC) [47]. The shaped signals from the MSCF-16 were sent to Mesytec MADC32 Analog to Digital Converters (ADCs). The online acquisition is performed using MIDAS [48]. A custom OpenGL-based graphical online acquisition software was used to observe incoming data during the experiment.

3.4 Targets

Figure 3.9 shows the target ladder with the different targets mounted. The main reaction target used during the experiment was ZnS ($178 \mu\text{g}/\text{cm}^2$) deposited on a thin carbon backing ($5 \mu\text{g}/\text{cm}^2$). In addition, data were taken using a self-supporting carbon foil ($20 \mu\text{g}/\text{cm}^2$), natural zinc foil ($1785 \mu\text{g}/\text{cm}^2$), and mylar foil ($(\text{C}_{10}\text{H}_8\text{O}_4)_n$) ($350 \mu\text{g}/\text{cm}^2$). The purpose of the additional targets were diagnostic and background identification/subtraction. The zinc, in the reaction target and the separate foil, is of natural isotopic composition and therefore contains multiple zinc isotopes (^{64}Zn 49.17%, ^{66}Zn 27.73%, ^{68}Zn 18.45%, and ^{67}Zn 4.04%). Due to the very different Q-values for (p,d) reactions on the zinc isotopes, the zinc was not a major source of background in the deuteron energy spectrum in the energy region of interest. However, the same can not be said about the carbon, which produced several peaks in the deuteron energy spectrum in the energy region of interest. In addition, due to the presence of water vapor, deuterons from the $^{16}\text{O}(p,d)^{15}\text{O}$ reaction are also present as background in the deuteron energy spectrum. Data taken with the carbon foil and mylar foil targets were analyzed similarly to the primary target data and the deuteron angular distributions from $^{12}\text{C}(p,d)^{11}\text{C}$ and $^{16}\text{O}(p,d)^{15}\text{O}$ reactions are used to reliably estimate the contribution from the background peaks in the deuteron energy spectrum.

In addition, the carbon target was particularly useful for diagnostic purposes and therefore was used periodically throughout the experiment. The relatively clean deuteron energy spectrum from the $^{12}\text{C}(\text{p},\text{d})^{11}\text{C}$ reaction, and well known structure in ^{11}C , made it possible to verify calibrations and track any gain drifts. Also, the carbon target was crucial in correcting for the beam offset, as described in Appendix B.

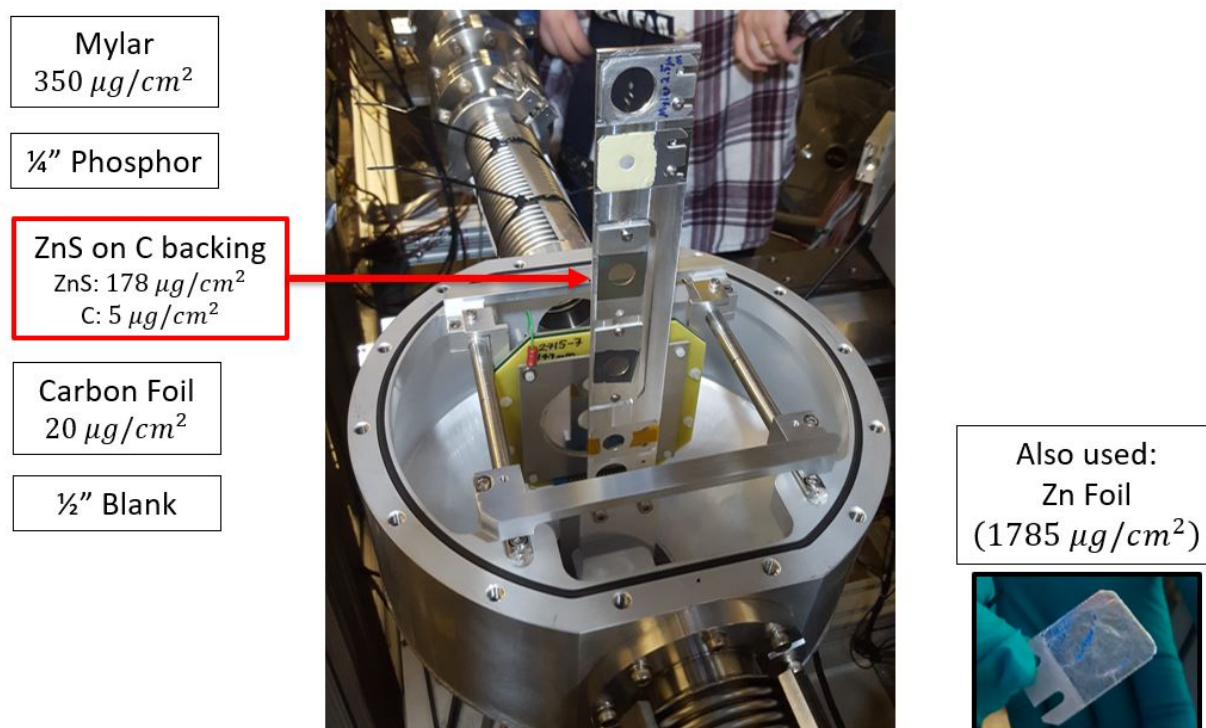


Figure 3.9: Image of the target ladder with the targets mounted as used during the experiment. Towards the end of the experiment the Mylar target was replaced by the Zn foil.

Chapter 4

Data Analysis Methods

4.1 Nuclear Reaction Kinematics

A standard notation for writing nuclear reaction is $X(a,b)Y$. This notation describes a beam-like nucleus ‘a’ interacting with a stationary target-like nucleus ‘X’ resulting in the light nucleus ‘b’, which is called the ejectile, and ‘Y’, the heavy recoil nucleus. A diagram describing the kinematics of such a reaction is shown in Figure 4.1.

The Q -value for a nuclear reaction is the difference between the final and initial kinetic energy of the nuclei involved in the reaction. The Q -value represents the amount of mass converted into binding energy of the nucleus or vice-versa. A reaction with a positive Q -value releases energy while a reaction with a negative Q -value converts energy into mass. Due to the mass-energy equivalence, the Q -value can also expressed as the difference between the initial and final masses of the nuclei involved in the reaction. Therefore, using the notation from Figure 4.1 we can express the Q -value in the following ways.

$$Q = T_Y + T_b - T_X - T_a \quad (4.1)$$

$$Q = M_X c^2 + M_a c^2 - M_Y c^2 - M_b c^2 \quad (4.2)$$

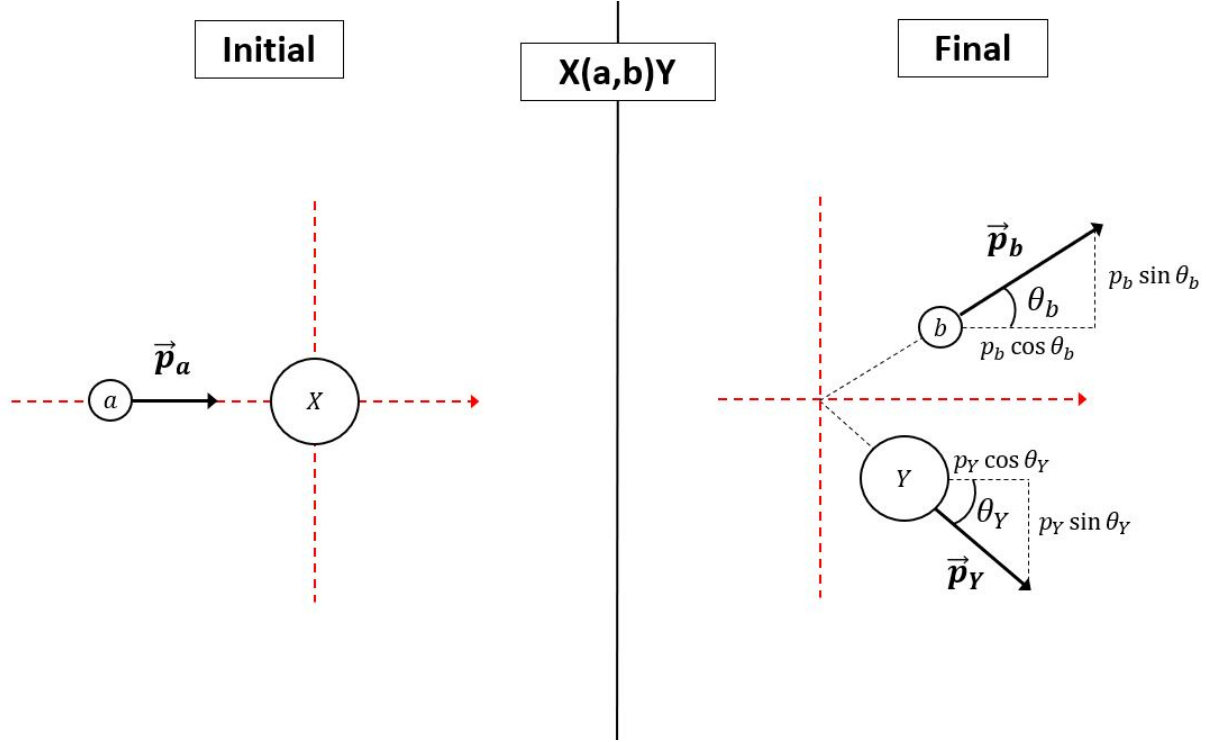


Figure 4.1: Kinematics diagram for a nuclear reaction $X(a,b)Y$ in the laboratory frame. The left panel represents the initial state, prior to the reaction, and the right panel shows the final state, following the reaction.

It is convenient to express the conservation of linear momentum in a nuclear reaction along two axes, one parallel and one perpendicular to the beam direction. These can be referred to as the longitudinal and transverse direction respectively. Conservation of linear momentum in the longitudinal and transverse directions is given by the following equations.

$$p_a = p_b \cos \theta_b + p_Y \cos \theta_Y \quad (4.3)$$

$$0 = p_b \sin \theta_b - p_Y \sin \theta_Y \quad (4.4)$$

where p_i is the non-relativistic linear momentum of particle i .

Combining Equation 4.3, Equation 4.4, and Equation 4.1, it is possible to arrive at an expression for the Q -value for the nuclear reaction populating a state with some excitation energy that is a function of the masses of the nuclei involved, the beam energy, the ejectile energy, and the ejectile angle. This expression is given in Equation 4.5. If the masses of the

nuclei involved in the reaction are known beforehand and the beam energy is also known, then the energy and angle of the ejectile can be used to determine the Q -value for populating the final state in the recoil nucleus. Subtracting this calculated Q -value from the Q -value for populating the ground state produces the excitation energy of the final state in the recoil nucleus. This assumes that the ejectile is not produced in an excited state, which is the case for light ejectiles with only one bound state such as a deuteron. In the case of the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction, we will use the measured energy and angle of the outgoing deuteron to calculate the excitation energy of the final state in ^{31}S populated by the reaction. This will be done using the the following Q -value equation,

$$Q = \frac{1}{m_Y}((m_Y + m_b)T_b - (m_Y + m_a) - \sqrt{m_a m_b T_a T_b} \cos \theta_b). \quad (4.5)$$

The Q in Equation 4.5 is the Q -value for populating an excited state in the final nucleus. The difference between the Q -value for populating the ground state of the final nucleus and the Q given in Equation 4.5 is the excitation energy of the state populated. The Q -value for populating the ground state is known if the masses of the nuclei involved are known.

4.2 Nuclear Decay Kinematics

The nuclear states of interest to this work are very short-lived and are populated by a nuclear reaction. Therefore, the recoiling nucleus has a non-zero velocity in the laboratory frame when it decays. The magnitude and direction of the velocity of the recoiling nucleus in the laboratory frame must be taken into account when reconstructing the decay in order to reconstruct the energy of the decay in the rest frame of the recoiling nucleus. For this analysis, we have assumed that the recoiling nucleus decayed while traveling with a velocity equal to the velocity it had immediately following the reaction. This assumption is valid because the lifetimes of nuclear states are much shorter than the timescale of the recoil losing energy while moving through the target. The nuclear states of interest to this work decay by either proton, or γ -ray emission. In the case of particle emission, the method is very similar to the kinematics described in the previous section. In the case of γ -ray emission,

the detected γ -rays will be Doppler shifted due to the fact that they were emitted from a moving source.

4.2.1 Particle Emission from a Moving Source

Consider a nucleus ‘X’, the parent nucleus, which has a non-zero velocity in the laboratory frame. The parent nucleus then decays via particle emission into ‘Y’ and ‘b’, where ‘b’ is the light decay particle and ‘Y’ is the daughter nucleus (these are not the same particles X, Y, and b described in Section 4.1). In the center-of-mass frame, the decay particle and daughter nucleus will always travel away with a relative angle of 180° . However, in the laboratory frame, the final velocity of the two decay products will be boosted in the direction of the initial velocity of the parent nucleus. A schematic of this process is shown in Figure 4.2.

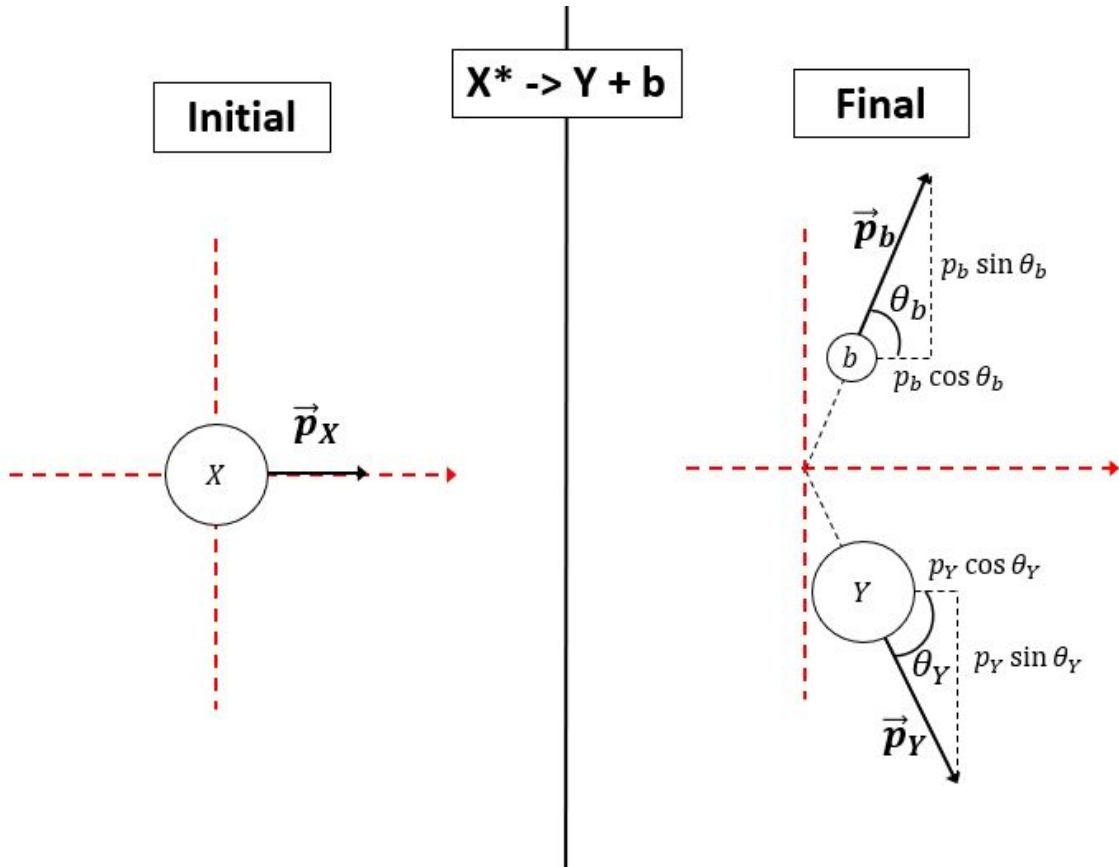


Figure 4.2: Kinematics diagram, in the laboratory frame, of particle emission from a nucleus with non-zero velocity. The left panel represents the initial state, prior to the decay, and the right panel shows the final state, following the decay.

In the center-of-mass frame, the parent nucleus is at rest. Therefore, the initial kinetic energy is zero. Following the decay, both the decay particle and daughter nucleus will have some kinetic energy. The sum of these two kinetic energies is the decay Q -value (Equation 4.6). In the case of proton emission from an excited nuclear state, the Q -value would be equal to the difference in the excitation energy of the parent nucleus and the proton separation energy.

$$Q = T_Y + T_b \quad (4.6)$$

In the center-of-mass frame, the initial state has zero momentum and therefore, conservation of linear momentum tells us that the daughter nucleus and decay particle will have equal and opposite momenta.

$$\vec{p}_b = -\vec{p}_Y \quad (4.7)$$

Using these two equations, it is possible to express the energy of the decay particle in the center-of-mass frame in terms of the masses of the decay products and the decay Q -value.

$$T_b = \frac{m_Y}{m_b + m_Y} Q \quad (4.8)$$

In the center-of-mass frame, the decay particle will always have the same energy regardless of the direction of emission. However, in the laboratory frame, the energy of the decay particle will depend on the angle of emission with respect to the initial velocity of the parent nucleus. Due to the fact that the laboratory frame is not the center-of-mass frame, to properly reconstruct the energy of decay, and therefore identify the final state populated in the daughter nucleus, the kinematics of the decay must be taken into account.

For the specific case of the $^{32}\text{S}(p, d)^{31}\text{S}^*(p)^{30}\text{P}$ reaction and proton decay, conservation of energy and momentum can be used to arrive at Equation 4.9 for the excitation energy of the final state in ^{30}P populated by the proton decay. A complete derivation of Equation 4.9 can be found in Appendix C.

$$E_{ex, ^{30}\text{P}} = E_r - \frac{1}{M_{^{30}\text{P}}} \left((M_{^{30}\text{P}} + M_p)T_p - (M_{^{31}\text{S}^*} - M_{^{30}\text{P}})T_{^{31}\text{S}^*} - 2\sqrt{M_{^{31}\text{S}^*}M_p T_{^{31}\text{S}^*}T_p} \cos \theta_{p, ^{31}\text{S}^*} \right) \quad (4.9)$$

Where E_r is the resonance energy, which is the difference between the ^{31}S excitation energy and ^{31}S proton separation energy (as shown in Figure 2.2),

$$E_r = E_{ex,^{31}\text{S}} - S_p(^{31}\text{S}). \quad (4.10)$$

The angle $\theta_{p,^{31}\text{S}^*}$ is the angle between the velocity of the decay proton and the velocity the recoiling $^{31}\text{S}^*$. Plotting $E_{ex,^{30}\text{P}}$ as calculated in Equation 4.9 versus the ^{31}S excitation energy produces a proton-decay matrix. A proton-decay matrix can be used to identify proton-decay branches from specific states in ^{31}S . An example of a proton-decay matrix is shown in Chapter 5.

4.2.2 γ -ray Emission from a Moving Source : The Doppler Effect

When a photon is emitted from a moving source, a stationary observer will observe the photon at a different energy than the energy with which it was emitted in the rest frame of the source. This is known as the relativistic Doppler effect. In the case of γ -ray de-excitation of a recoiling nucleus, the γ -ray detectors are the stationary observers and the recoiling nucleus is the moving source. The energy of a γ -ray measured by a detector will be shifted by a certain amount depending on the angle between the velocity of the recoil and opening of the detector. The energy of the γ -ray must be corrected for this shift to get the energy of the transition in the recoil nucleus. The formula for the relation between the observed energy and actual energy is,

$$E_{source} = E_{observed} \frac{1 + \beta \cos \theta}{\sqrt{1 - \beta^2}}. \quad (4.11)$$

where β is the magnitude of the velocity of the recoil nucleus divided by the speed of light and θ is the angle between the velocity of recoil and the γ -ray detector.

The Hyperion array has γ -ray detectors positioned around the target chamber, and therefore detections are possible at a large range of angles between the recoil nucleus and the detected γ -ray. When the angle between the γ -ray and the velocity of the recoil is less than

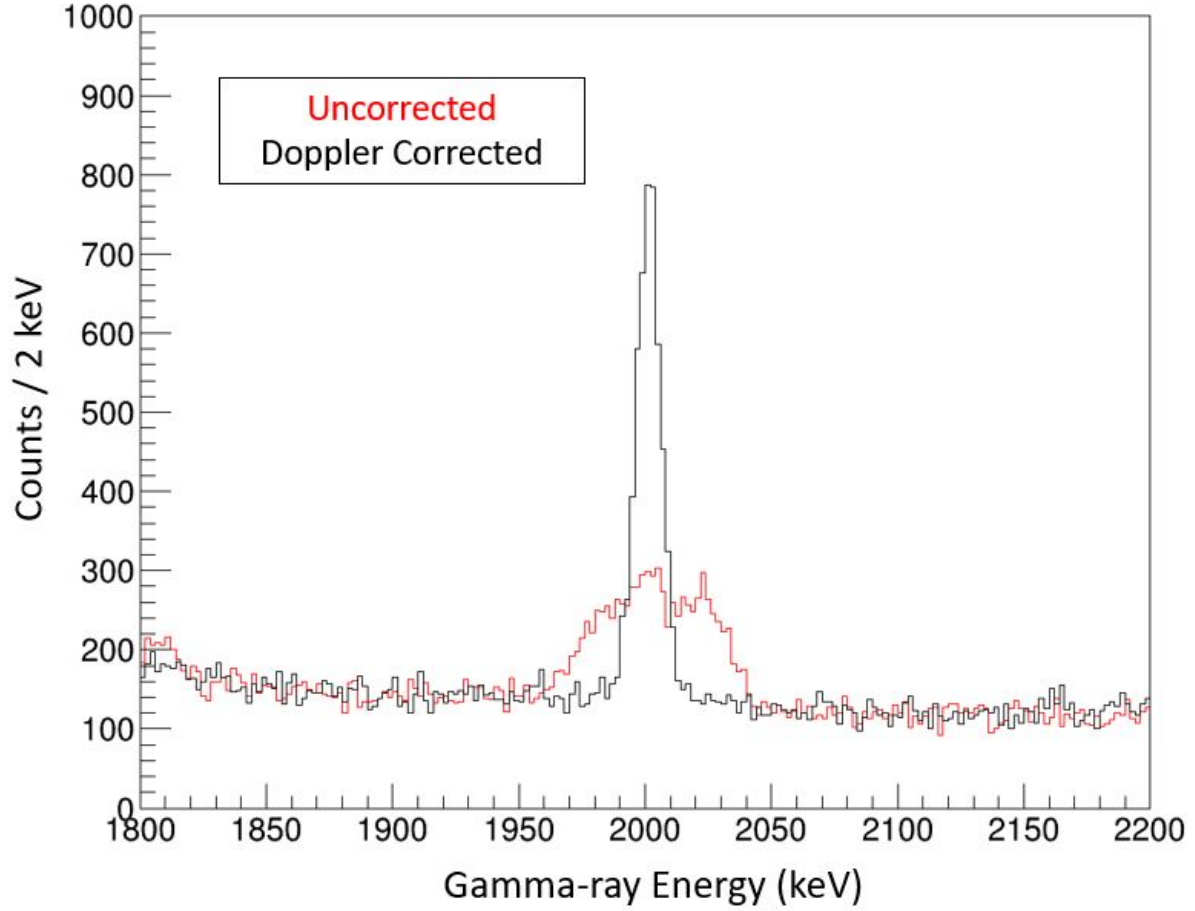


Figure 4.3: γ -ray peak from the de-excitation of the first excited state in ^{11}C following the $^{12}\text{C}(p, d)^{11}\text{C}$ reaction. The black spectrum has been corrected for the Doppler shift while the red spectrum is uncorrected.

90° , the γ -ray is detected at a higher energy in the laboratory frame than it has in the rest frame of the recoil. Conversely, when this angle is greater than 90° , the γ -ray is detected with less energy. This leads to a spreading of γ -ray peaks in an uncorrected spectrum. In Figure 4.3, the γ -ray spectrum from the de-excitation of the first excited state in ^{11}C following the $^{12}\text{C}(p, d)^{11}\text{C}$ reaction is shown. The red spectrum has not been corrected for the Doppler shift and the black has been corrected.

4.3 Deuteron Decay-Proton Angular Correlations

If we imagine a nucleus excited to a state above the threshold for particle emission, in the rest frame of this nucleus the distribution of emitted particles would be isotropic as no preferred direction in space exists. If we consider the case of two successive radiations, then the first fixes a direction in space, and the angle of the second emitted radiation with respect to the first will exhibit a shape characteristic of the angular momentum of the states involved and the emitted radiation [49]. The angular correlation can be defined as the intensity of the decay as a function of the angle between the two radiations. [49]. In the case that a particle-unbound excited nuclear state was created by a nuclear reaction, an angular correlation will exist between the ejectile of the reaction and the emitted decay particle. In the case of $^{32}\text{S}(p, d)^{31}\text{S}^*(p)^{30}\text{P}$, there will be an angular correlation between the deuteron and decay-proton emitted from $^{31}\text{S}^*$. The angular correlation can be described by an expansion of even-order Legendre polynomials [49],

$$W(\theta_{d-p}^{CoM}) = \sum_{n=0,2,4,\dots} \frac{1}{4\pi} (a_n P_n(\cos \theta_{d-p}^{CoM})). \quad (4.12)$$

where, in the absence of the knowledge of the J^π of the final or initial state, the coefficients a_n are left as free parameters in a fit to the data. The maximum term n included in the fit is related to the orbital angular momentum carried away by the proton by $n = 2l$. The goodness of the fit is determined by a statistical significance test using the p -value. To carry out this test, a null hypothesis is defined: first an isotropic ($n = 0$) fit, corresponding to an $l = 0$ decay was chosen. The p -value is the probability that a value chosen at random from the chi-square probability distribution would be greater than or equal to the observed value if the null hypothesis were true [43]. It is customary in statistical analysis to use a p -value of 0.05 to determine statistical significance [50]. Therefore, if the $n = 0$ fit returns a p -value > 0.05 , the null hypothesis is accepted. If the p -value is < 0.05 , then the null hypothesis is rejected. The next order term would then be included and the test would be repeated. The lowest value of n that passes the p -value test is used to assign l_{min} . Including higher orders will increase the number of free parameters, and will tend to increase the quality of

the fit. Therefore fits using higher orders can not be rejected, but lower order fits can be. This leads to the assignment of a minimum l for the decay, l_{min} , and decays of higher angular momentum are not ruled out.

4.3.1 Proton Detection Efficiency

To plot the deuteron decay-proton angular correlations that were discussed in the previous section, the efficiency for detecting a reaction-deuteron decay-proton coincidence as a function of the angle between them in the reaction center-of-mass frame must be known. The efficiency for detecting a decay proton in coincidence with a deuteron was calculated using a Monte Carlo simulation. The simulation was developed specifically for this experiment but could readily be adapted for use in different setups consisting of different particle emitting nuclei and detector arrays mounted in different geometries. The general steps of the algorithm are:

1. Select a specific proton-unbound state populated in the $^{32}\text{S}(p,d)^{31}\text{S}^*$ reaction. This defines the decay Q-value.
2. Select a deuteron trajectory (segment in the silicon telescope). This defines the magnitude and velocity of the $^{31}\text{S}^*$ recoil and therefore the conversion between the decay center-of-mass frame and the laboratory frame.
3. Generate a random direction for the velocity of the decay proton in the decay center of mass frame.
4. Boost the velocity of the decay proton into the laboratory frame.
5. Trace the trajectory of the decay proton in the laboratory frame and determine if it hit the upstream detector.
6. Boost the velocity of the decay proton into the reaction center of mass frame.
7. Calculate the angle between the velocity of the deuteron produced in the reaction and the velocity of the decay proton in the reaction center of mass frame.

8. Record the angle between the deuteron and the decay proton and whether or not the proton hit the upstream detector (was detected).
9. Repeat Steps 2-7 N times, where N is proportional to the number of deuterons measured with this trajectory, in the excitation energy range of interest.
10. Repeat Steps 2-8 for every possible deuteron trajectory (telescope segment).

For each possible angle between the velocities of the decay proton and deuteron, divide the number of decay protons that hit the upstream detector by the total number of protons released. The result is the efficiency of detecting a decay proton as a function of the angle between the velocities of the decay proton and deuteron in the reaction center-of-mass frame. The output of the simulation can be found in Figure 4.4, which shows the distribution for the total number of decay protons and only the decay protons that were detected. Figure 4.5 shows the efficiency for detecting a decay proton in coincidence with a deuteron as a function of the angle between the velocities of the decay proton and deuteron in the reaction center-of-mass frame. Both Figure 4.4 and Figure 4.5 are the results for the state at $E_{ex} = 7.036$ MeV.

4.3.2 Proton-Decay Branching Ratios

The deuteron decay-proton angular correlation plots are plotted with the y-axis value in proton decays / steradian / number of times the resonance was formed. First, the raw deuteron decay-proton counts are plotted versus the angle between them in the reaction center-of-mass frame (See Figure 4.6). Next, the number of counts in each angular bin is divided by the efficiency for detecting a deuteron decay-proton coincidence with that angle and the solid angle covered by that angular bin. The result is a histogram containing the total number of decay protons / steradian. Lastly, the number of counts in every bin is divided by the number of times the resonance was formed, which is measured from the intensity of the corresponding peak in the deuteron singles spectrum. Proton-decay branching ratios are extracted using the deuteron decay-proton angular correlation plot and Equation 4.12. Once a suitable fit to angular correlation data is obtained using Equation 4.12, the angular

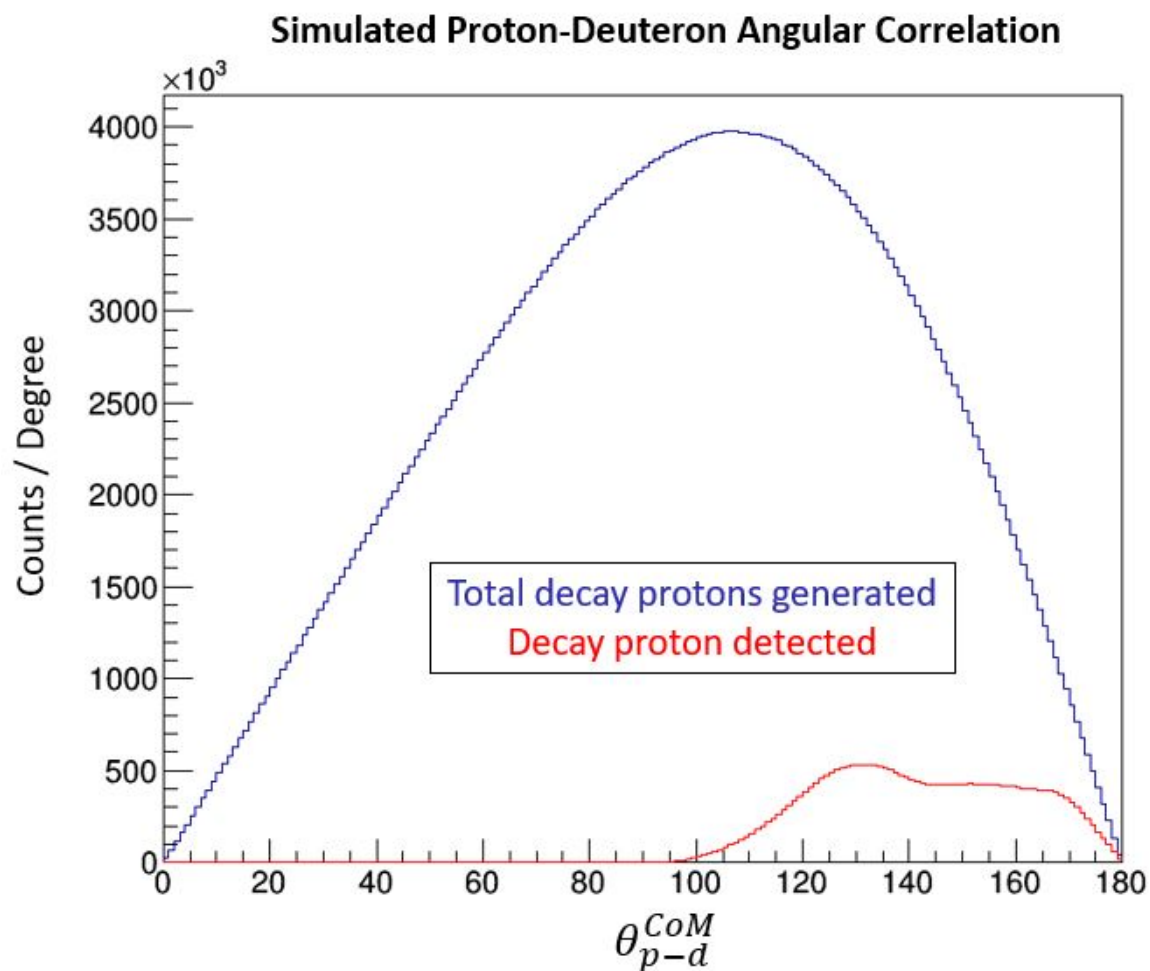


Figure 4.4: Histograms showing the total number of decay protons generated (blue) and the number of decay protons detected (red) as a function of the angle between the velocities of the decay proton and deuteron in the reaction center of mass frame.

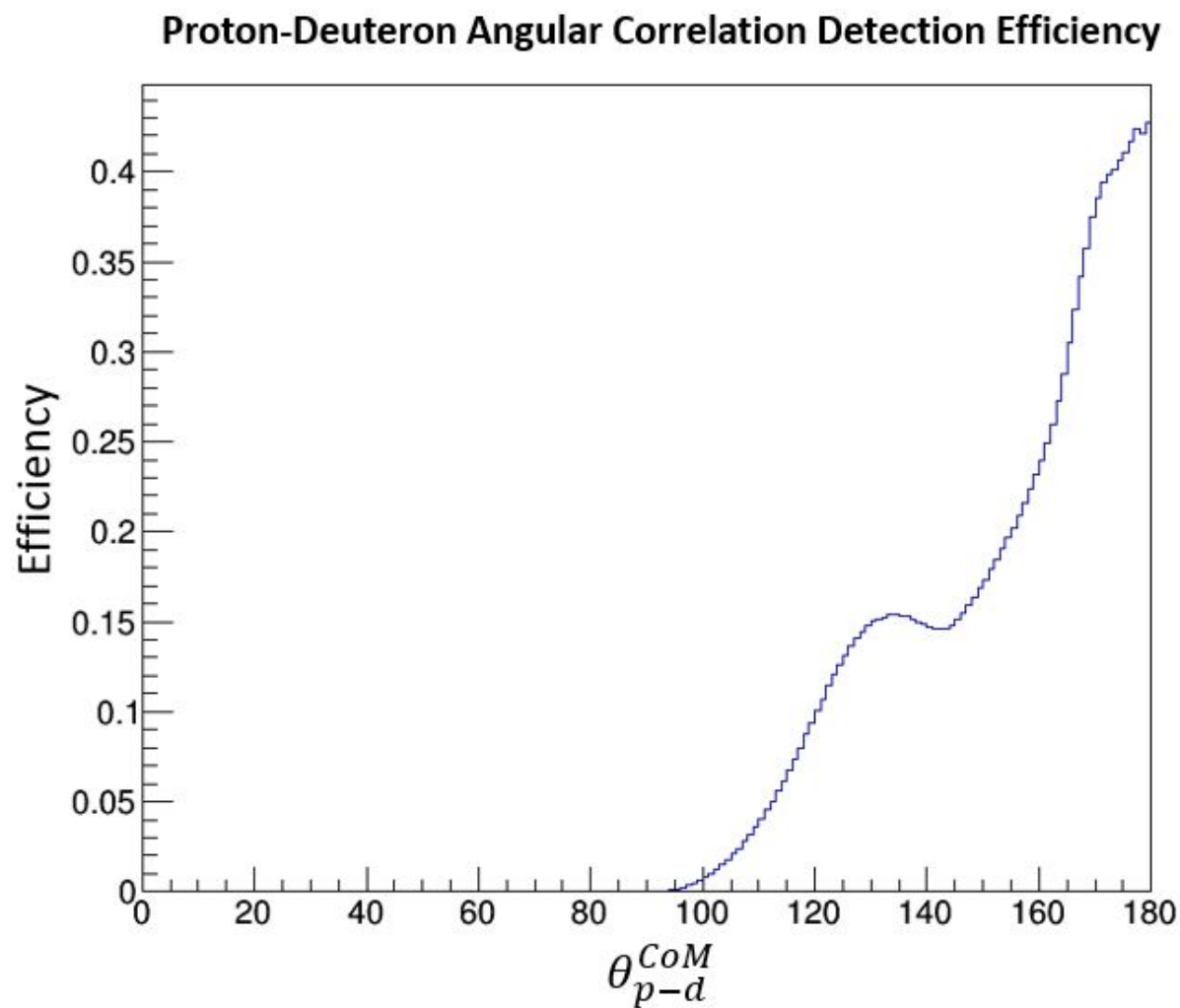


Figure 4.5: Histogram showing the efficiency for detecting a decay proton in coincidence with a deuteron as a function of the angle between the velocities of the decay proton and deuteron in the reaction center-of-mass frame.

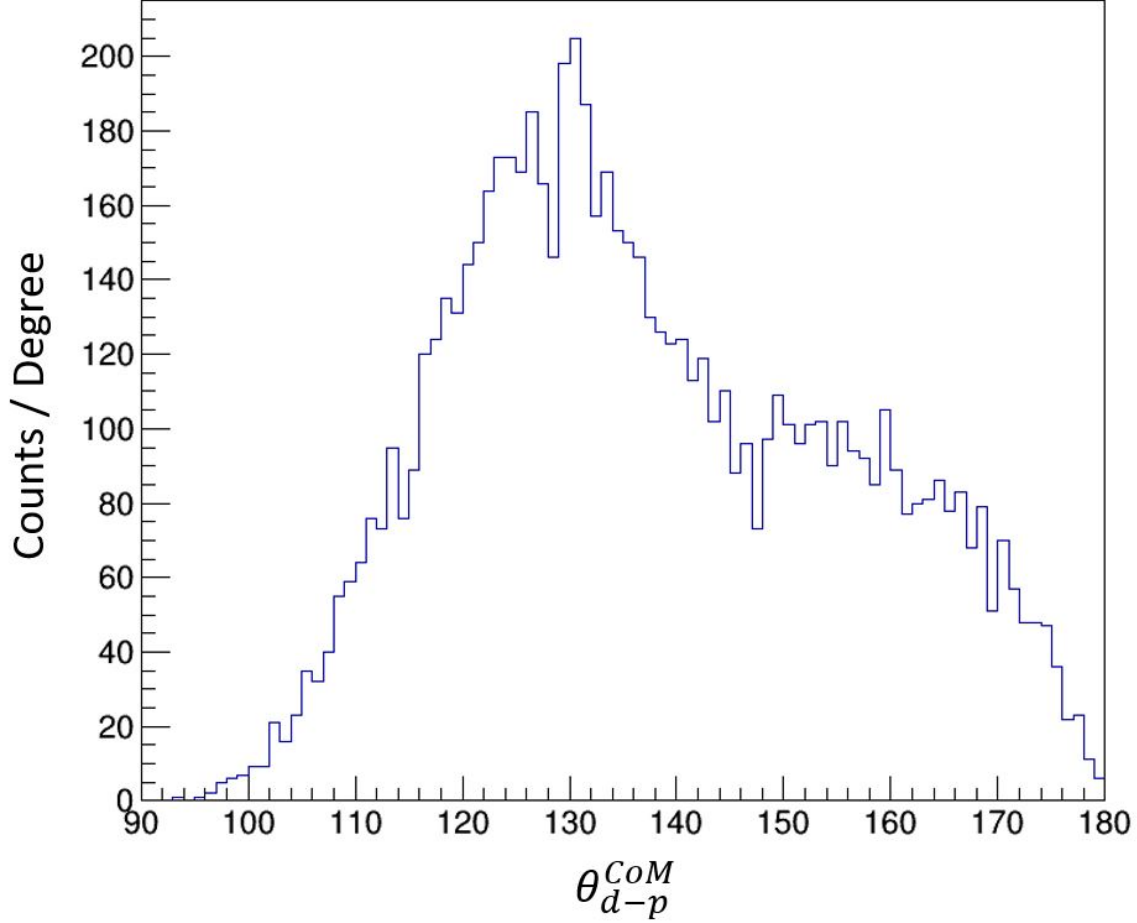


Figure 4.6: The raw number of deuteron decay-proton coincidences detected for the $E_{ex} = 7.036$ MeV state, uncorrected for efficiency and solid angle, as a function the angle between them in the reaction center-of-mass frame (θ_{d-p}^{CoM})

correlation function is then integrated from $\theta_{d-p}^{CoM} = 0 - 180^\circ$. The result of the integration is the proton-decay branching ratio.

4.4 Distorted Wave Born Approximation

The Distorted Wave Born Approximation (DWBA) is a method for calculating properties of scattering processes by treating the initial and final wave functions as combinations of incoming and outgoing plane and spherical scattered waves interacting with a central potential. DWBA can be used to calculate the differential cross section for transfer reactions such as the (p, d) reaction. The shape of the differential cross-section depends on the amount

of angular momentum transferred to the nucleus in the reaction. By comparing the shape of the differential cross-section, calculated using DWBA, to data it is possible to deduce the amount of transferred angular momentum.

To extract accurate results from DWBA, a suitable potential must be chosen. Typically an effective potential is constructed using the optical model. The optical model treats the incident particle as a wave scattering in a medium with a potential described by a real and imaginary component [51]. This is analogous to the refraction or absorption of a photon scattering in medium with a complex index of refraction. The real component of the optical model potential describes the nuclear potential and is a Woods-Saxon function. The imaginary component is an absorptive term that represents non-elastic processes and is often represented by a surface term described by the derivative of the real component, which results in a function that is strongly peaked at the nuclear surface.

Both the real and imaginary components of the optical model potential have a depth, radius, and diffuseness. Appropriate values for optical model parameters (OMPs) must be chosen for a DWBA calculation to yield accurate results. The appropriate OMPs depend on the nuclei involved and the energy at which the reaction will be measured. The incoming and outgoing channels each require their own set of OMPs. Elastic scattering data involving the nuclei present in the incoming or outgoing channel, and measured at the corresponding energy, can be used to extract a set of OMPs. The differential cross section for elastic scattering is measured and the data are fit with the OMPs left as free parameters. In the absence of elastic scattering data from the exact nuclei involved in the reaction of interest, OMPs derived from nearby nuclei may be used.

Chapter 5

Results and Discussion

In this chapter, the results from the experiment are presented followed by a discussion of the interpretation of the results for each resonant state. First, the results from the deuteron spectrum will be shown. This includes the full deuteron singles spectrum, identification of background peaks, and the measured deuteron angular distributions. Next, the γ -ray data are shown in a particle- γ matrix and a gate on a resonant state is used to extract the γ -ray transitions corresponding to its de-excitation. Finally, the results from the proton decays are shown. Deuteron decay-proton angular correlations are shown and comparisons are made with previous data where possible.

5.1 Deuteron Spectrum

Deuterons were selected using a 2D gate drawn in the PID plot as described in Chapter 3. Using the angular information, provided by the segmentation of the silicon telescope, the deuteron energy is plotted versus the angle at which it was detected. The result is shown in Figure 5.1. The discrete bands seen are associated with the population of different states in the final nucleus. Bands with different slopes correspond to (p, d) reactions on different nuclei. Using Equation 4.5 to calculate the Q-value, Figure 5.1 can be plotted with the ^{31}S excitation energy on the y-axis, as shown in Figure 5.2. In Figure 5.2, the horizontal bands correspond to states in ^{31}S populated via the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction and the curved bands correspond to states in ^{11}C and ^{16}O populated via the $^{12}\text{C}(p, d)^{11}\text{C}$ and $^{16}\text{O}(p, d)^{15}\text{O}$

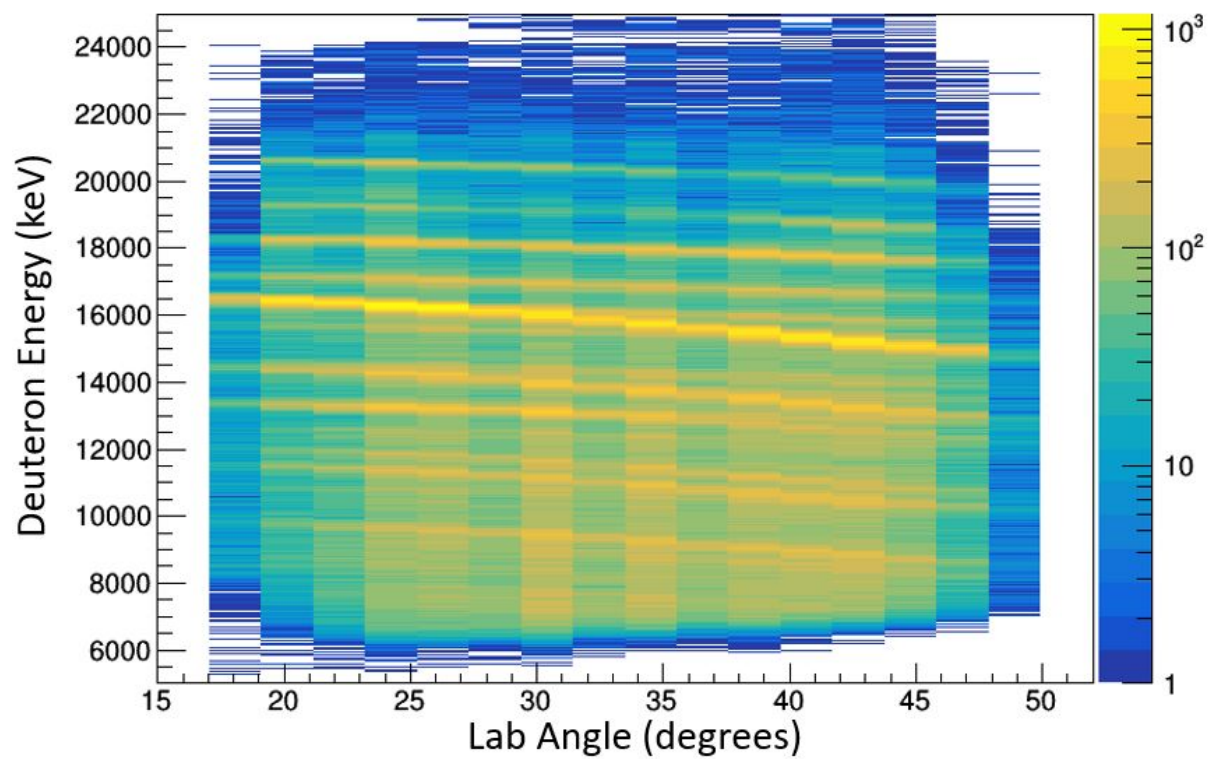


Figure 5.1: Deuteron energy versus angle as measured by the silicon telescope. This plot is made using a 2D gate on deuterons as described in Chapter 3.

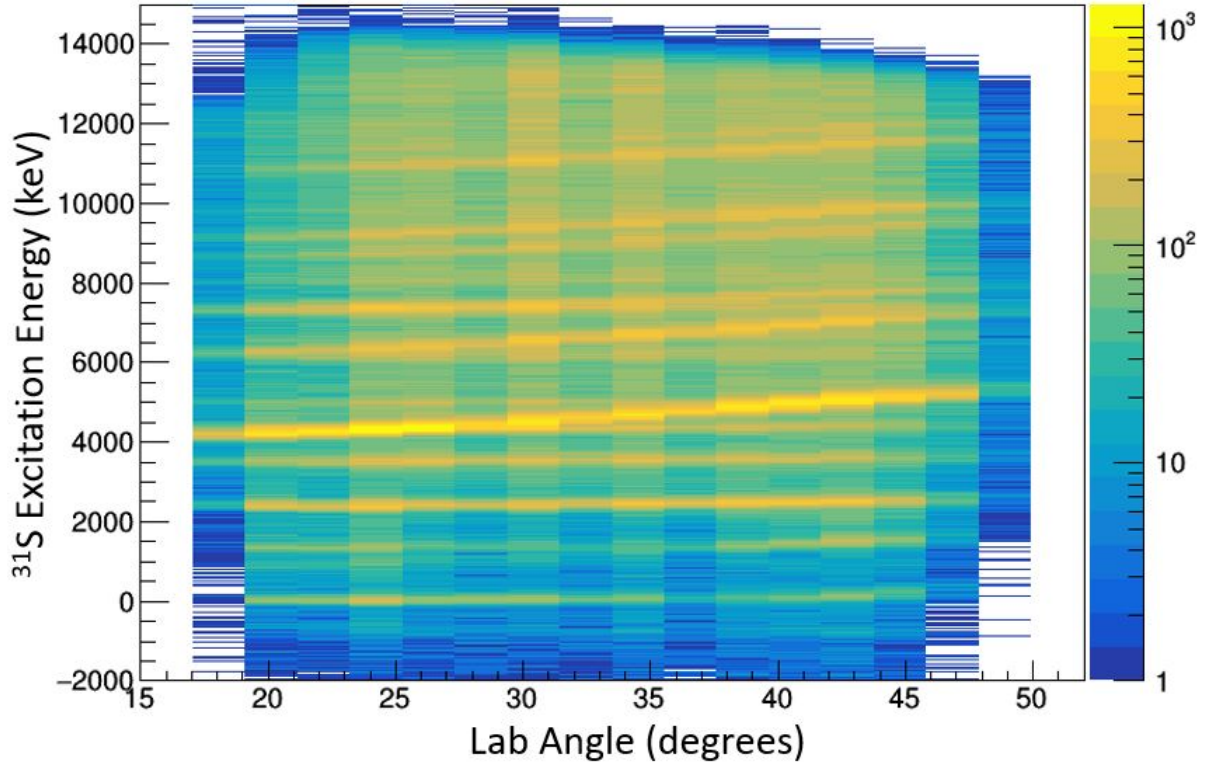


Figure 5.2: ^{31}S excitation energy versus angle as measured by the silicon telescope. This plot is made using a 2D gate on deuterons as described in Chapter 3. The ^{31}S excitation energy is calculated using Equation 4.5.

reactions respectively and also (p, d) reactions on stable Zn isotopes. Plotting the deuteron spectrum in this way assumes that the deuteron came from the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction. When this assumption is incorrect, the result is curved bands due to the different masses of the nuclei involved.

The deuteron singles spectrum is used to determine the states in ^{31}S populated in the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction. The deuteron singles spectrum, shown in Figure 5.3, is generated by projecting the entire 2D histogram found in Figure 5.2 onto the y-axis. Some of the structure seen in the spectrum in Figure 5.3 originates from the $^{12}\text{C}(p, d)^{11}\text{C}$ and $^{16}\text{O}(p, d)^{15}\text{O}$ reactions as well as (p, d) reactions on all of the stable Zn isotopes, as explained above. Using data taken with the mylar $((\text{C}_{10}\text{H}_8\text{O}_4)_n)$ and Zn foils, the contributions to the deuteron singles spectrum coming from (p, d) reactions other than the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction can be identified. Figure 5.4 shows the same deuteron singles spectrum from Figure 5.3 with spectra recorded

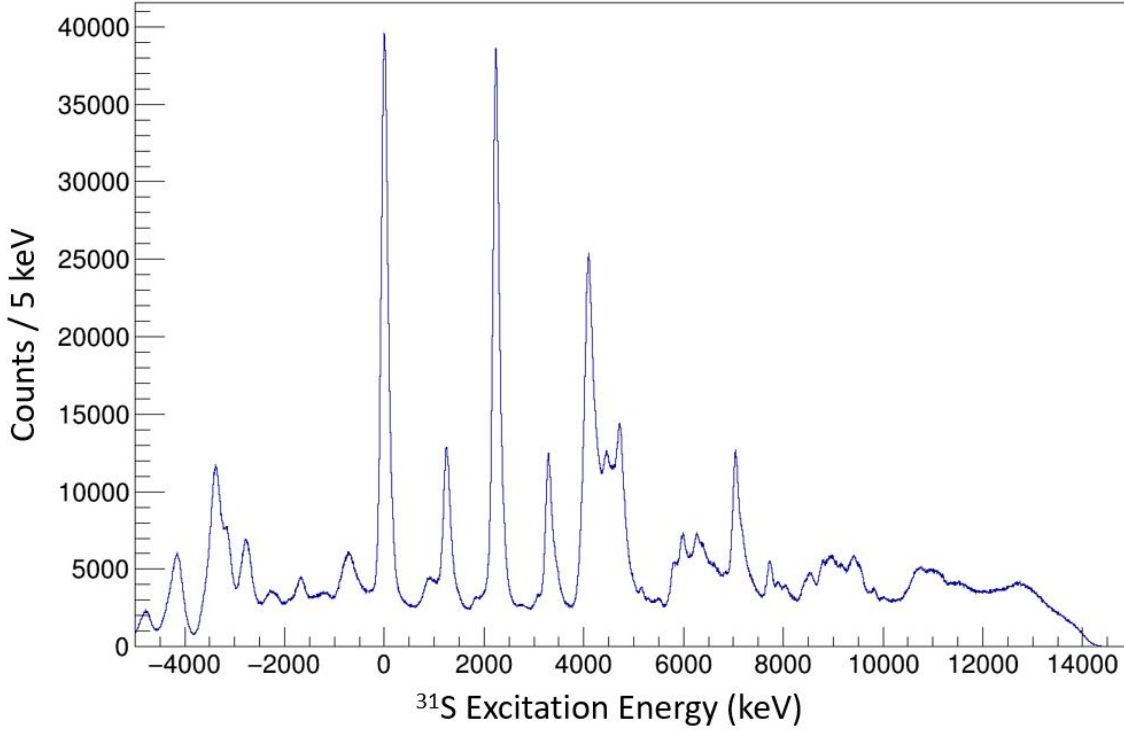


Figure 5.3: Deuteron spectrum from (p,d) reactions on the target consisting of ZnS deposited on a carbon backing summed over all angles. The x-axis is shown in calculated ^{31}S excitation energy using Equation 4.5.

with mylar and Zn targets overlayed. Some of the peaks in the spectrum are solely due to (p,d) reactions on Zn, C, or O, while others are combinations of a peak from the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction and one of these other (p,d) reaction.

To measure the γ -ray or decay-proton branching ratio for a state, it is necessary to know how many times the state was populated. To do this accurately, the background contributions from (p,d) reactions on nuclei other than ^{32}S must be taken into account. First, the reaction producing the interfering background peak was identified. Then the intensity as a function of angle (angular distribution) of the background peak was measured using data from one of the background target foils. In the case of the background due to the $^{12}\text{C}(p,d)^{11}\text{C}$ or $^{16}\text{O}(p,d)^{15}\text{O}$ reactions, the mylar target foil was used. Next, for angles in which there was clear separation between the background peak and the peak of interest, the peaks in the region were fit using two or more Gaussians on a linear background. The angular distribution of the background peak was then normalized to its intensity from the

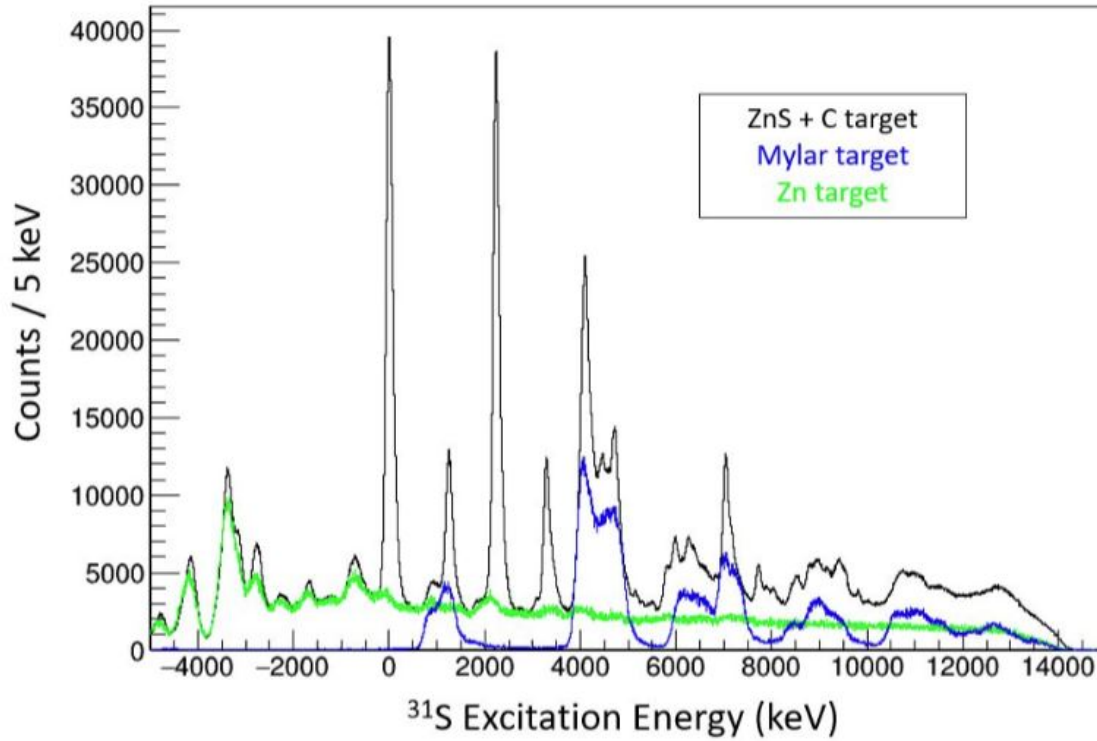


Figure 5.4: Deuteron spectrum from (p,d) reactions on the target consisting of ZnS deposited on a carbon backing, summed over all angles. The x-axis is shown in calculated ^{31}S excitation energy using Equation 4.5. The contributions from (p,d) reactions with C and O is shown in blue and was measured using the mylar target. The contributions from (p,d) reactions with Zn isotopes is shown in green and was measured using a Zn target foil of natural isotopic purity. The Zn target and Mylar target spectra are normalized by the number of counts in the transfer to the ground state for the $^{64}\text{Zn}(p,d)^{63}\text{Zn}$ and $^{12}\text{C}(p,d)^{11}\text{C}$ reactions respectively.

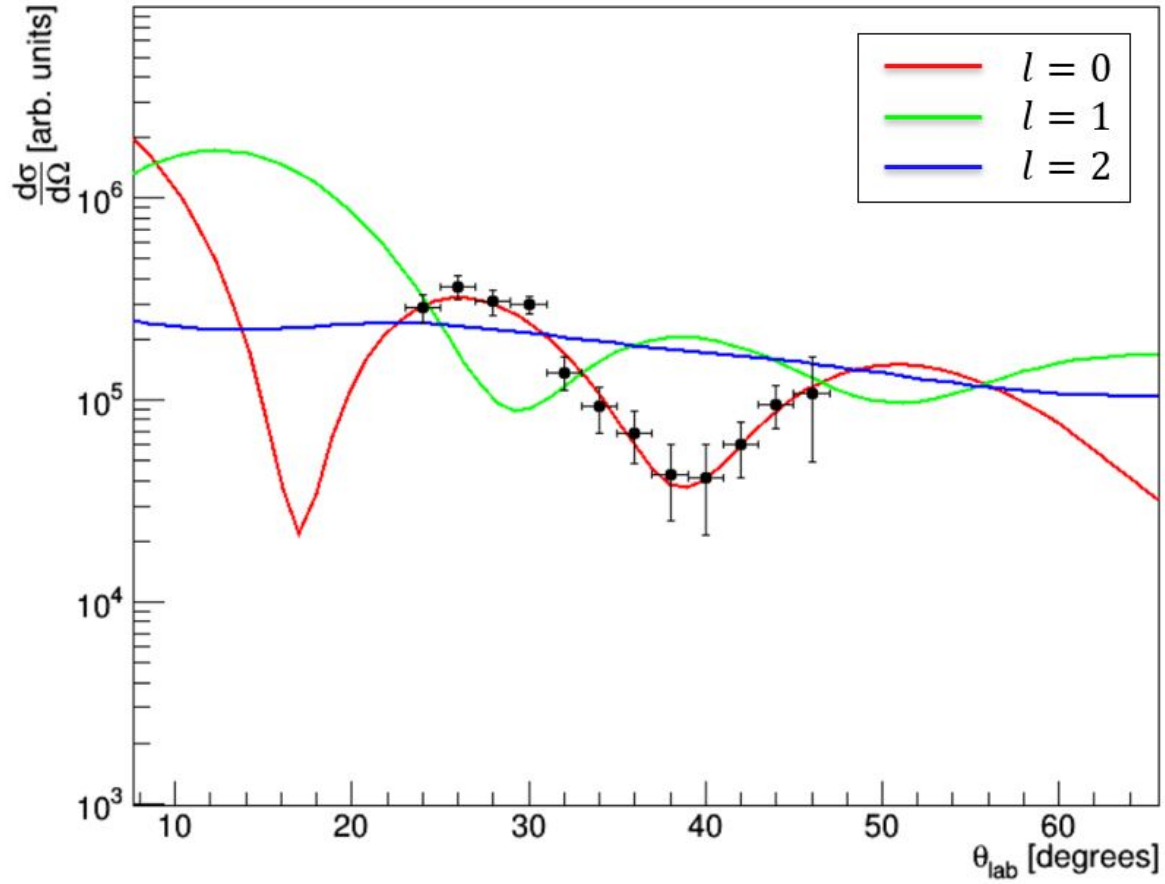


Figure 5.5: The differential cross section as a function of angle for the $^{32}\text{S}(p, d)^{31}\text{S}$ reaction populating the ground state of ^{31}S . The different colored curves are DWBA calculations for different amounts of transferred angular momentum. Good agreement is found with an $l = 0$ transfer.

fits at these clean angles. The normalized angular distribution was then used to constrain the intensity of the background peak at angles in which there was not clear separation with the peak of interest. In addition to constraining the intensity of background peaks, the expected location of the background peak was calculated as a function of angle and then used to constrain its location when it overlapped with the peak of interest. Known energies from the $^{12}\text{C}(p, d)^{11}\text{C}$ or $^{16}\text{O}(p, d)^{15}\text{O}$ reactions were used to verify the energy calibration of the silicon telescope.

Table 5.1: Optical Model and neutron bound state Parameters used for the DWBA analysis. The three rows correspond to the parameters used for the incoming proton channel, the outgoing deuteron channel and the binding potential of the transferred neutron in ^{32}S . The proton parameters were obtained from Kozub et al [2] and the deuteron parameters from Cowley et al [3]. Standard values were used for the neutron parameters.

	$r_c(\text{fm})$	$V_0(\text{MeV})$	$r_0(\text{fm})$	$a_0(\text{fm})$	$V_i(\text{MeV})$	$r_i(\text{fm})$	$a_i(\text{fm})$
p	1.18	47.1	1.18	0.66	6.87	1.18	0.66
d	1.18	90.0	1.25	0.62	25.0	1.30	0.58
n			1.20	0.65			

5.1.1 Distorted Wave Born Approximation Analysis

To help constrain the spin-parity of states populated in the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction, the angular distributions of the reaction deuterons were compared to DWBA calculations. The DWBA calculations for this analysis were performed using the code TWOFNR [52]. The optical model parameters used for these calculations were taken from a study by Kozub [2]. Kozub performed (p,d) reactions on all of the $N=Z$ nuclei in the 2s-1d shell and found good agreement with DWBA calculations for the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction. The incoming proton optical parameters were extracted from proton elastic scattering on ^{36}Ar measured in the same study. The outgoing deuteron parameters were obtained from a study by Cowley et al. [3]. The optical model parameters used in the DWBA calculations for this analysis can be found in Table 5.1. An example of using DWBA calculations to compare to data and infer the angular momentum transferred can be found in Figure 5.5, where the angular distribution for the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction to the ground state of ^{31}S is shown. The data shows good agreement with the DWBA calculation for $l = 0$ transfer. The initial and final states are known to have spin-parities of $J^\pi = 0^+$ and $J^\pi = 1/2^+$ respectively and therefore the identification of $l = 0$ is correct. Figures 5.7 to 5.9 show the angular distributions for the 6872(2), 7036(7), and 7171(8) keV states. In this region of excitation energy there was a background peak from the $^{16}\text{O}(p,d)^{15}\text{O}$ reaction to a state with $E_{ex} = 6176.3(17)$ keV. Figure 5.6 shows the location of the peaks in the ^{31}S excitation energy spectrum as a function of laboratory angle. The intensity of the background peak was accounted when extracting the intensity of the states in ^{31}S using the procedure described in Section 5.1.

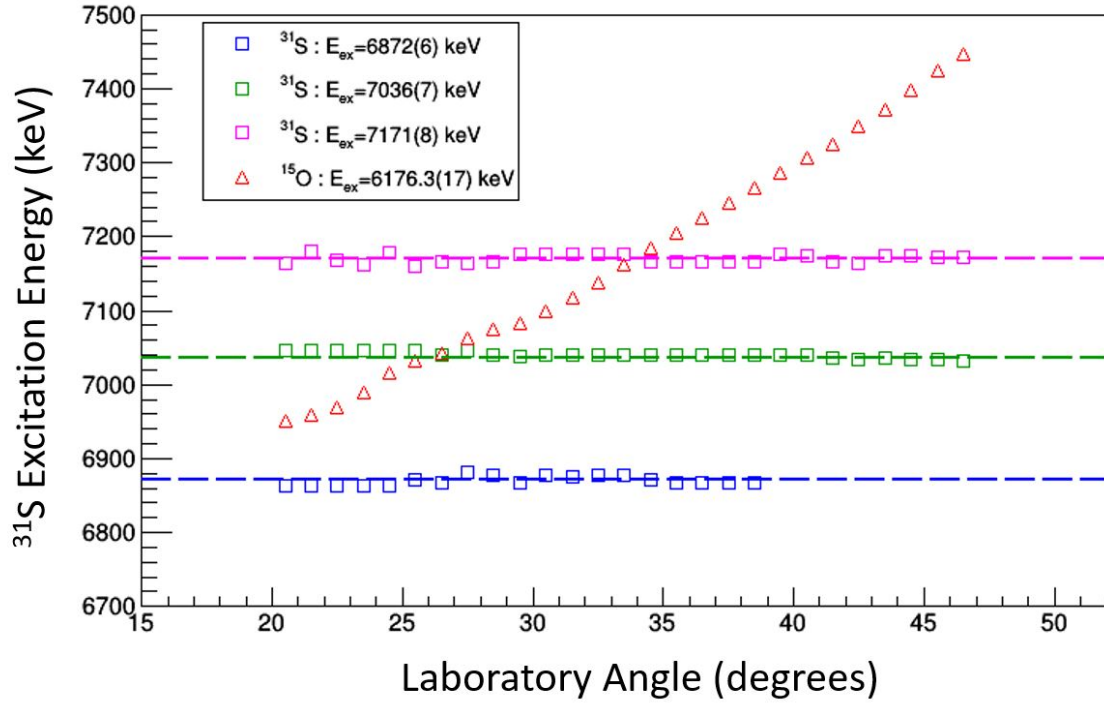


Figure 5.6: The location of the centroids as a function of laboratory angle for three peaks corresponding to states in ^{31}S (open squares), and a background peak from the $^{16}\text{O}(p, d)^{15}\text{O}$ reaction to a state with $E_{\text{ex}} = 6176.3(17)$ keV (open triangles). The horizontal dotted lines correspond to the excitation energies measured in this work for these three states in ^{31}S .

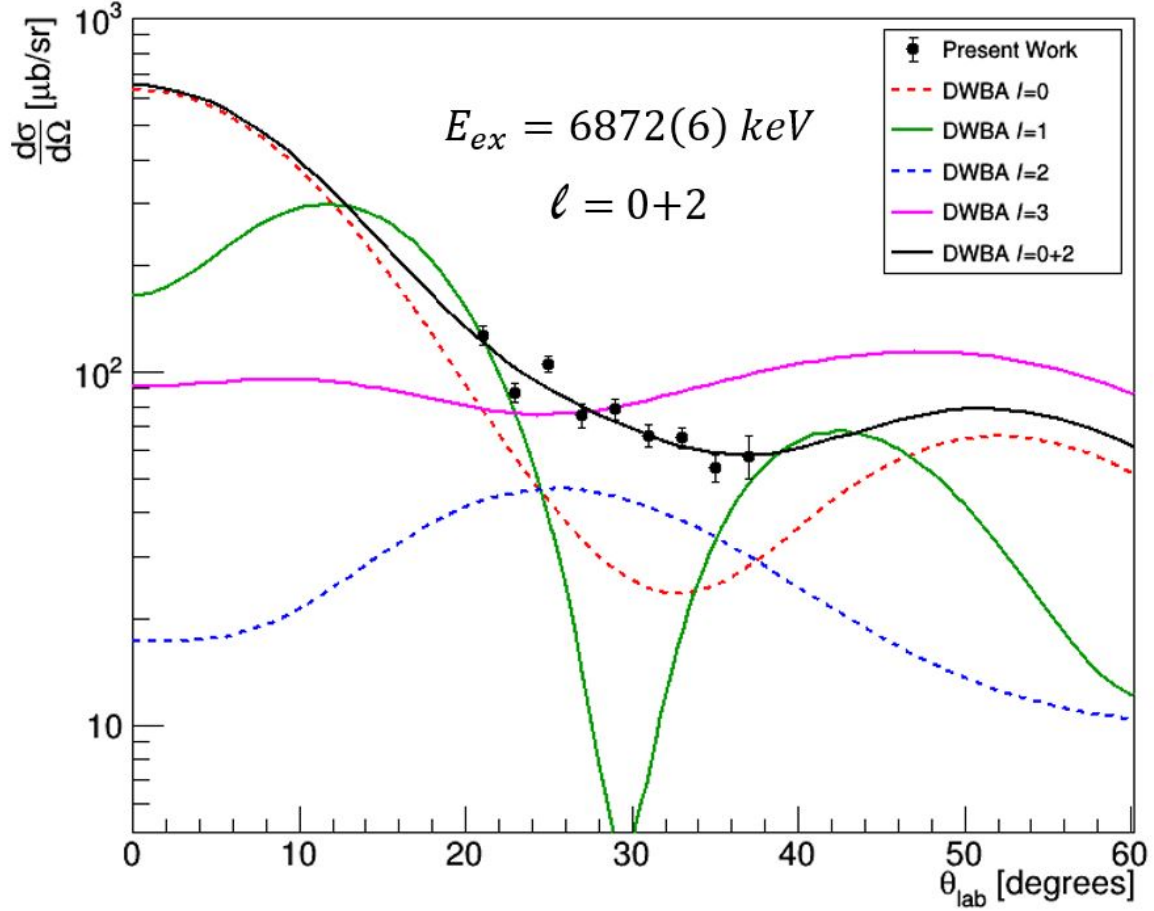


Figure 5.7: Angular distribution of deuterons populating the 6872(6) keV state. The solid black circles are the data points measured in this experiment. The curves are DWBA calculations for various angular momentum transfers. The black curve was found to agree well with data, and represents a sum of the $l = 0$ and $l = 2$ curves, assuming an equal contribution. The data from the present work has been normalized to Kozub et al. using the same scaling factor extracted from the 7036(7) keV state.

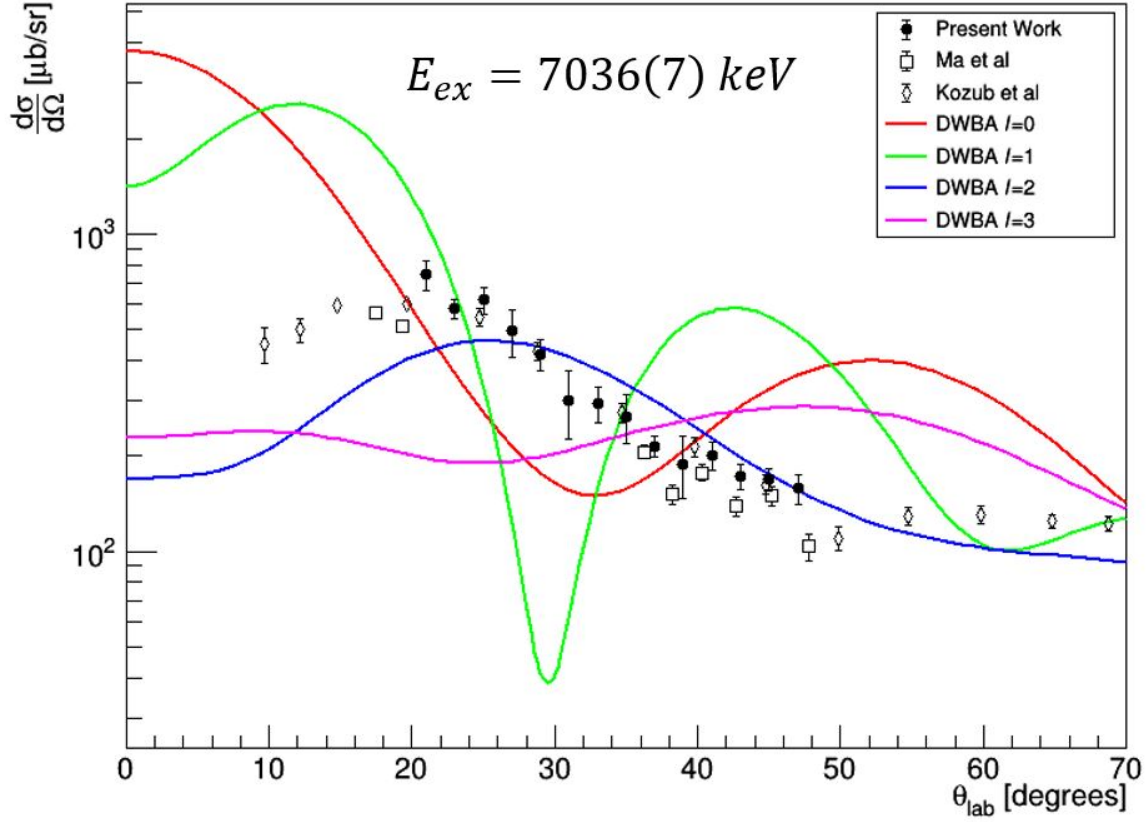


Figure 5.8: Angular distribution of deuterons populating the 7036(7) keV state. The solid black circles are the data points measured in this experiment. Two previous data sets from the same reaction are overlayed in the open square and open diamonds[13, 2]. The solid curves are DWBA calculations for various angular momentum transfers. The data from the present work has been normalized to Kozub et al at $\theta_{lab} = 29$ degrees.

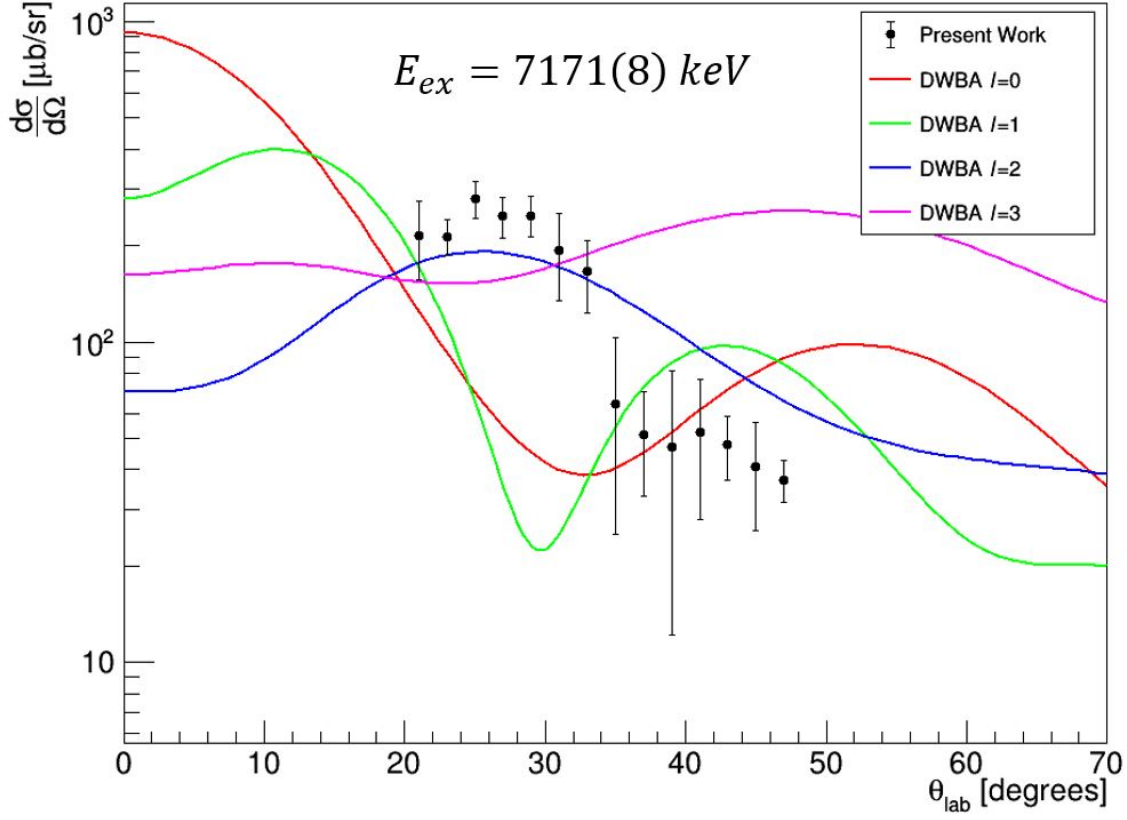


Figure 5.9: Angular distribution of deuterons populating the 7036(6) keV state. The solid black circles are the data points measured in this experiment. The solid curves are DWBA calculations for various angular momentum transfers. The data from the present work has been normalized to Kozub et al. using the same scaling factor extracted from the 7036(7) keV-state.

5.2 γ -ray De-excitations

5.2.1 Particle-Gamma Coincidence

To identify γ rays associated with states above the proton-separation energy, a particle- γ matrix was plotted. Figure 5.10 shows the particle- γ matrix recorded during the experiment. The y-axis is the Doppler-corrected γ -ray energy and the x-axis is the associated ^{31}S excitation energy as calculated from the coincident deuteron energy and angle. The red dotted line is drawn where the γ -ray energy is equal to the ^{31}S excitation energy. γ rays falling on this line correspond to transitions directly to the ground state of ^{31}S . The larger loci, which appear smeared out in both ^{31}S excitation energy and γ -ray energy, are γ -ray de-excitations from states in ^{11}C and ^{15}O populated via the $^{12}\text{C}(p,d)^{11}\text{C}$ or $^{16}\text{O}(p,d)^{15}\text{O}$ reactions, respectively.

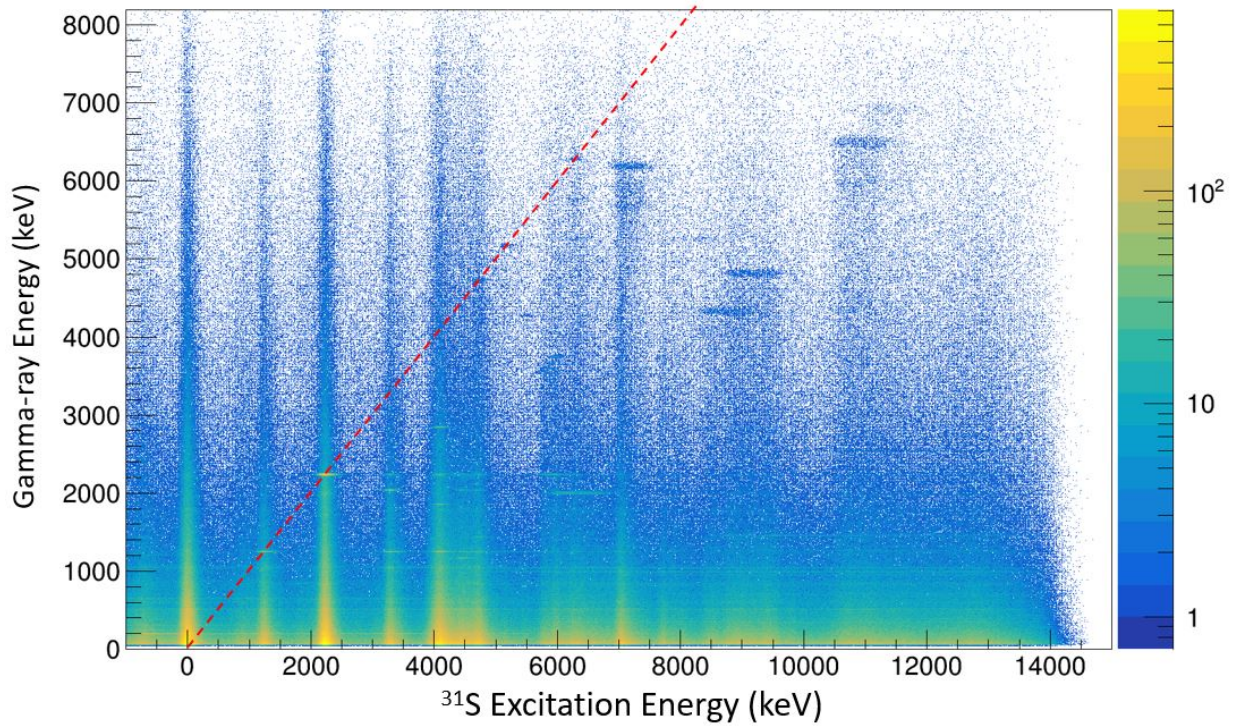


Figure 5.10: Particle- γ matrix. Two-dimensional histogram showing γ -ray energy plotted versus ^{31}S excitation energy. The red dotted line is drawn where the γ -ray energy is equal to the ^{31}S excitation energy. γ rays falling on this line correspond to transitions directly to the ground state of ^{31}S .

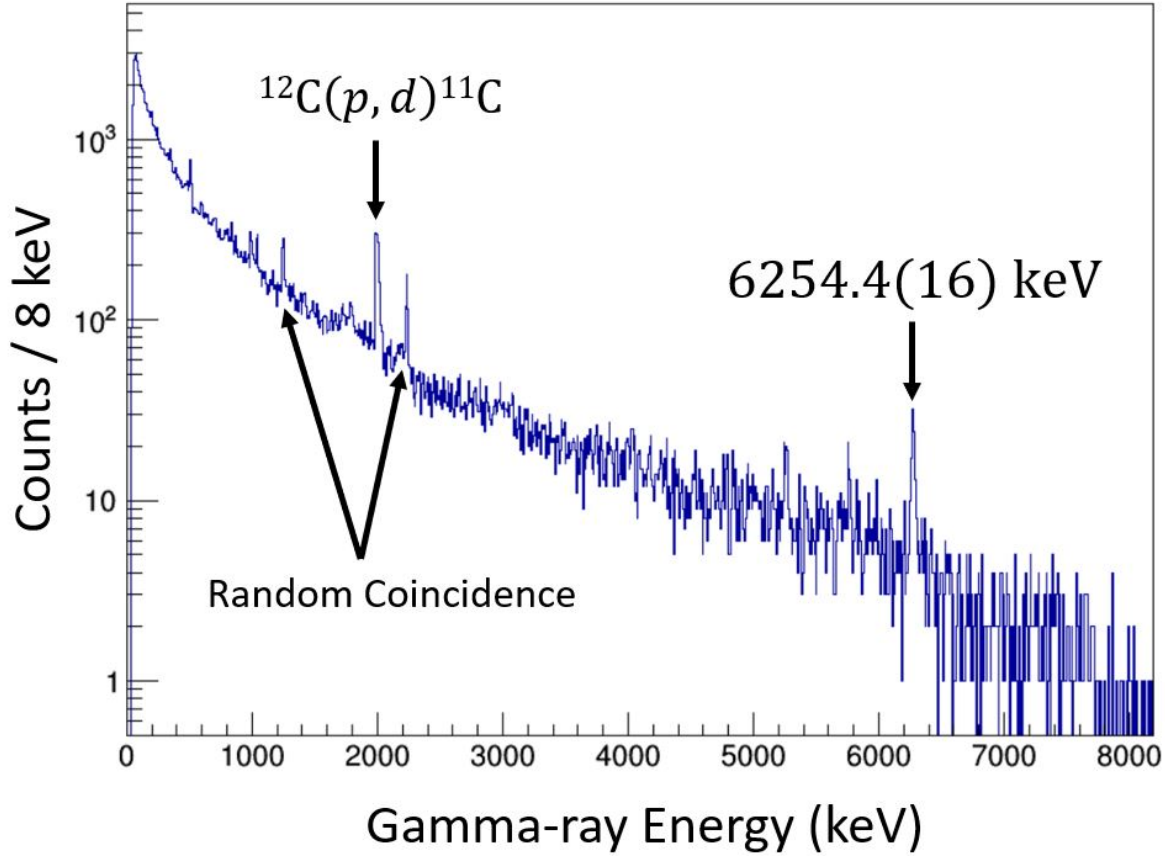


Figure 5.11: γ -ray spectrum in coincidence with the deuterons corresponding to an ^{31}S excitation energy of $E_{ex} = 6150 - 6350$ keV. A background peak from the de-excitation of the first excited state in ^{11}C is seen at 2000.0 keV. In addition, peaks corresponding to the de-excitation of the first and second excited states in ^{31}S , at 1248.9 keV and 2234.3 keV are observed. These γ -rays are collecting transitions in ^{31}S and are therefore attributed to random coincidences with deuterons populating the 6255.0 keV state.

Using Figure 5.10, gates were made in ^{31}S excitation energy to select a state of interest. All γ -ray counts falling in a gate are then projected onto the γ -ray energy axis (y-axis) and the resulting 1D histogram provides a clean measure of the γ -ray transitions associated with the de-excitation of the state of interest. In this experiment, one state above the proton separation energy with a γ -ray decay branch was observed (see Figure 5.11). The γ -ray was found to have an energy of $E_\gamma = 6254.4(16)$ keV and corresponds to a transition directly to the ground state in ^{31}S .

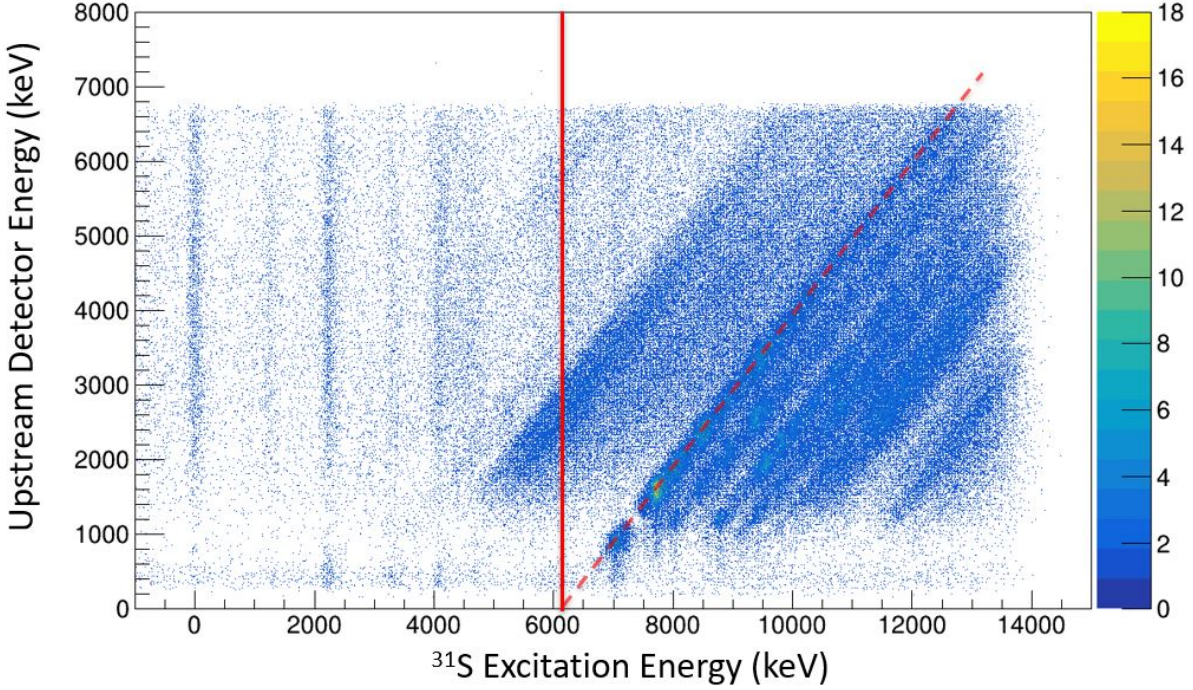


Figure 5.12: Proton decay matrix. The energy detected in the upstream detector is plotted versus the ^{31}S excitation energy for events in which a deuteron was measured in coincidence with an event in the upstream detector. A software threshold of 300 keV has been applied to the upstream detector remove counts due to noise from the spectrum. The vertical solid red line is drawn at the proton separation energy in ^{31}S and the sloped red dotted line is a line of equal energy originating from where the point where the solid line intersects the x-axis. Structures falling on the sloped line correspond to proton decays from states in ^{31}S to the ground state of ^{30}P and the parallel bands to the right correspond to proton decays from states in ^{31}S to excited states of ^{30}P . Structures falling to the left of the sloped line are not energetically possible for ^{31}S proton decay and therefore have a different origin. The slanted bands seen in this region are from proton decay from states in Zn isotopes. The vertical structure seen in this region are random coincidences with peaks in the deuteron spectrum.

5.3 Proton Decays

5.3.1 Proton Decay Matrix

Prior to this analysis, the state-of-the-art method for measuring proton-decays in coincidence with reaction products was constructing the matrix seen in Figure 5.12. This matrix plots the energy measured in the upstream (proton) detectors on y-axis versus the excitation energy of the proton emitting state in the recoil nucleus ^{31}S . In Figure 5.12, the vertical solid red line is drawn at the ^{31}S proton separation energy and the red dotted line

is a line of equal energy (slope = 1) intercepting the x-axis at the proton-separation energy. Structures falling on this line correspond to proton decays from states in ^{31}S to the ground state of ^{30}P and the parallel bands to the right correspond to proton decays from states in ^{31}S to excited states of ^{30}P .

Examples of the type of plot shown in Figure 5.12 can be found in many previous works [4, 53, 54]. These earlier examples were measurements in which only a limited range of angles between the recoil nucleus and decay proton were measured, due to the geometry of the setup. The setup used for this experiment was sensitive to a larger range of angles between the recoil nucleus and decay proton. This leads to a large spread in measured proton energy (~ 300 keV) in the laboratory frame for a specific decay branch. To be able to distinguish individual proton decay branches a new analysis method was developed.

The result of the new method is shown in Figure 5.13, where the energy of the final (daughter) state in ^{30}P , following the emission of a proton, is plotted against the energy of the initial (parent) state in ^{31}S , which was populated via the $^{32}\text{S}(p, d)^{31}\text{S}^*$ reaction. The values on the axes are calculated from the measured proton and deuteron energies and angles using the methods described in the Chapter 4. The corrected proton decay matrix can be used to identify the proton branches associated with specific states in ^{31}S .

From Figure 5.13 gates can be made in either the vertical or horizontal direction to extract different information. To generate Figure 5.14, horizontal gates were drawn on each of the individual final states in ^{30}P in Figure 5.13 and the counts in these gates were projected onto the ^{31}S excitation energy axis and then plotted with the deuteron single spectrum. The proton decay counts have been arbitrarily scaled such that the first large p_0 peak is normalized to the deuteron singles spectrum. From this Figure, the competition between the different proton-decay branches for a particular region of the ^{31}S excitation energy can be seen. For example, a particularly strong p_3 branch from a state at ~ 8800 keV is observed.

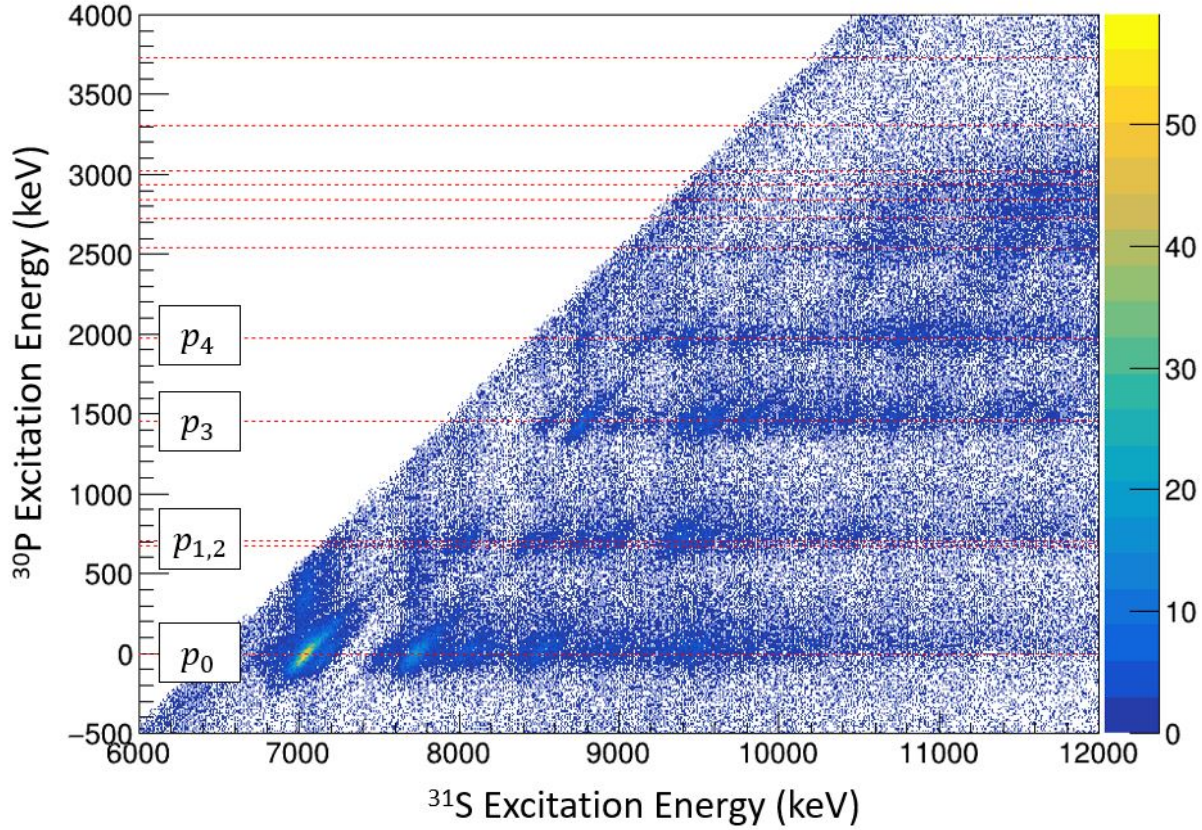


Figure 5.13: Corrected proton decay matrix. Two-dimensional histogram showing ^{30}P excitation energy versus ^{31}S excitation energy, where the ^{30}P excitation energy corresponds to the energy of state in ^{30}P populated by the proton decay from the excited state of ^{31}S . A software threshold of 300 keV has been applied to the upstream detector remove counts due to noise from the spectrum. The horizontal red-dotted lines represent known states in ^{30}P and are labeled with the corresponding proton decay branch from p_0 to p_4 .

To explore the relative intensities of different proton-decay branches from a specific state in ^{31}S , a vertical gate can be drawn around the region of excitation energy of the state of interest in Figure 5.13 and the counts in this gate are projected onto the ^{30}P excitation energy axis. In Figure 5.15, a gate was placed around a state at ~ 9400 keV in ^{31}S and the resulting proton spectrum is shown. While this state is much too high in energy to affect the reaction rate at nova temperatures, large p_0 through p_4 branches are all observed, illustrating the technique. The peak at the right hand side of the spectrum corresponds to low proton energy and is due to noise in the detector and not another proton-decay branch.

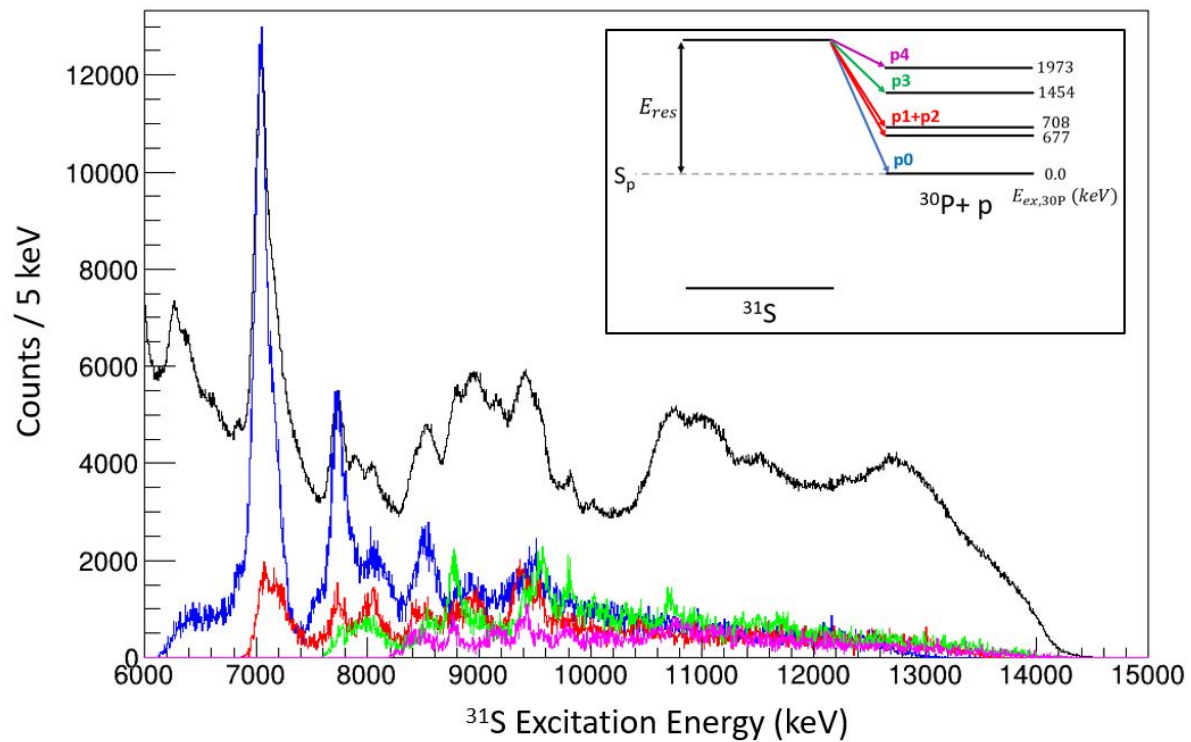


Figure 5.14: The region of the deuteron singles spectrum above the proton separation energy is shown in black. The overlaid colored histograms are deuteron and proton-decay coincidence spectra, where the different proton-decay branches are given different colors. The inset in the upper right contains a diagram where the arrows for the different proton-decay branches are colored to match the spectra shown.

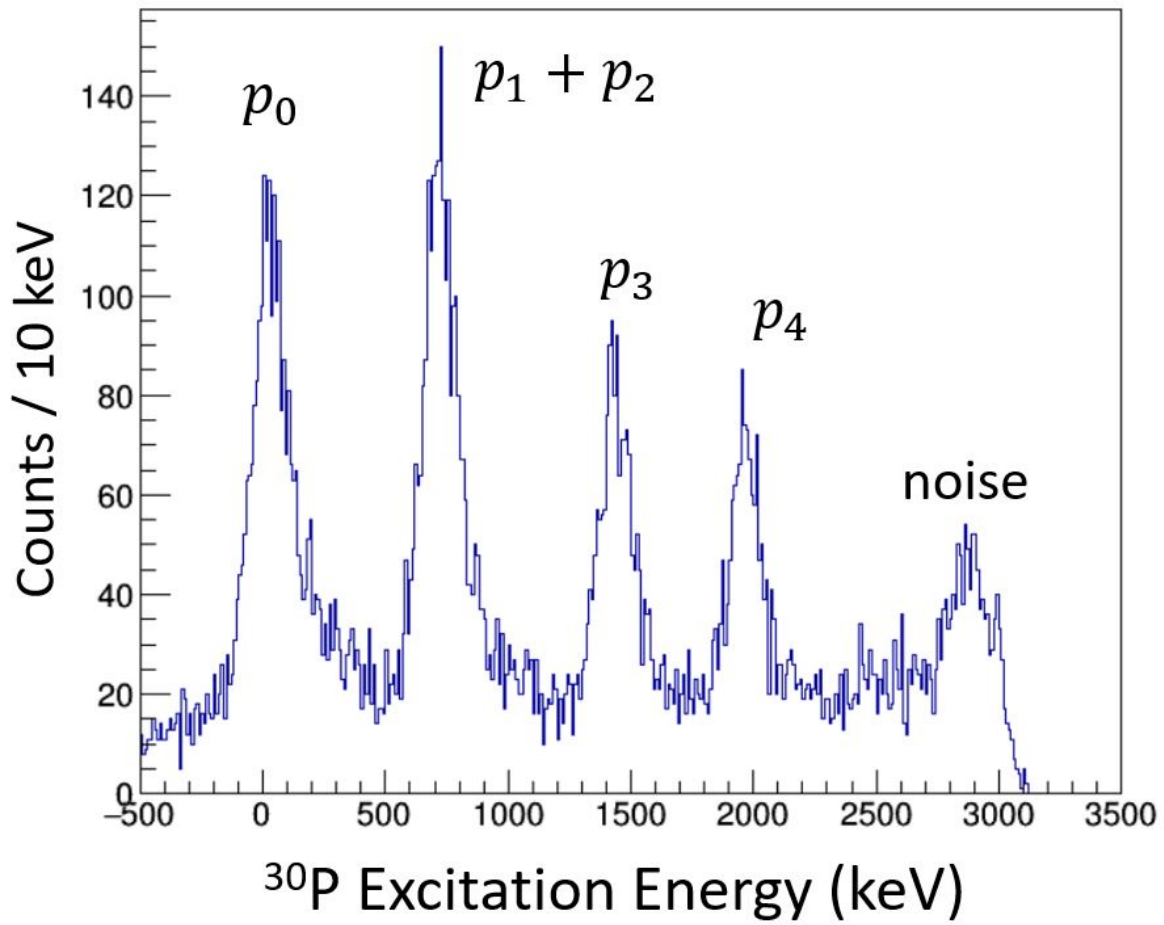


Figure 5.15: Proton decay spectrum of a state in ^{31}S at ~ 9400 keV. This state has strong proton-decay branches to the ground state and first four excited states in ^{30}P . The broad peak to the right-hand side of the spectrum is due to noise in the detector and not another proton-decay branch.

5.3.2 Deuteron Decay-Proton Angular Correlations

The deuteron decay-proton angular correlations were fit using Equation 4.12 and the procedure outlined in Chapter 4. For each state that was included in this analysis, the deuteron decay-proton angular correlation for the p_0 branch (Figures 5.16, 5.18, 5.20, 5.22, and 5.24) and a plot of the p -value versus the transferred angular momentum l (Figures 5.17, 5.19, 5.21, 5.23, and 5.25) are presented. For the 7036(7)-keV state, all of the fits for $l = 0 - 4$ are shown for comparison. The p -value versus l plots were used to determine l_{min} . When a discrete jump in p -value to above 0.05 was observed between two values of l , this was taken as strong evidence for the l_{min} assignment. The horizontal red dotted lines on the p -value versus l plots represents the 0.05 cutoff used to in this work to assign l_{min} .

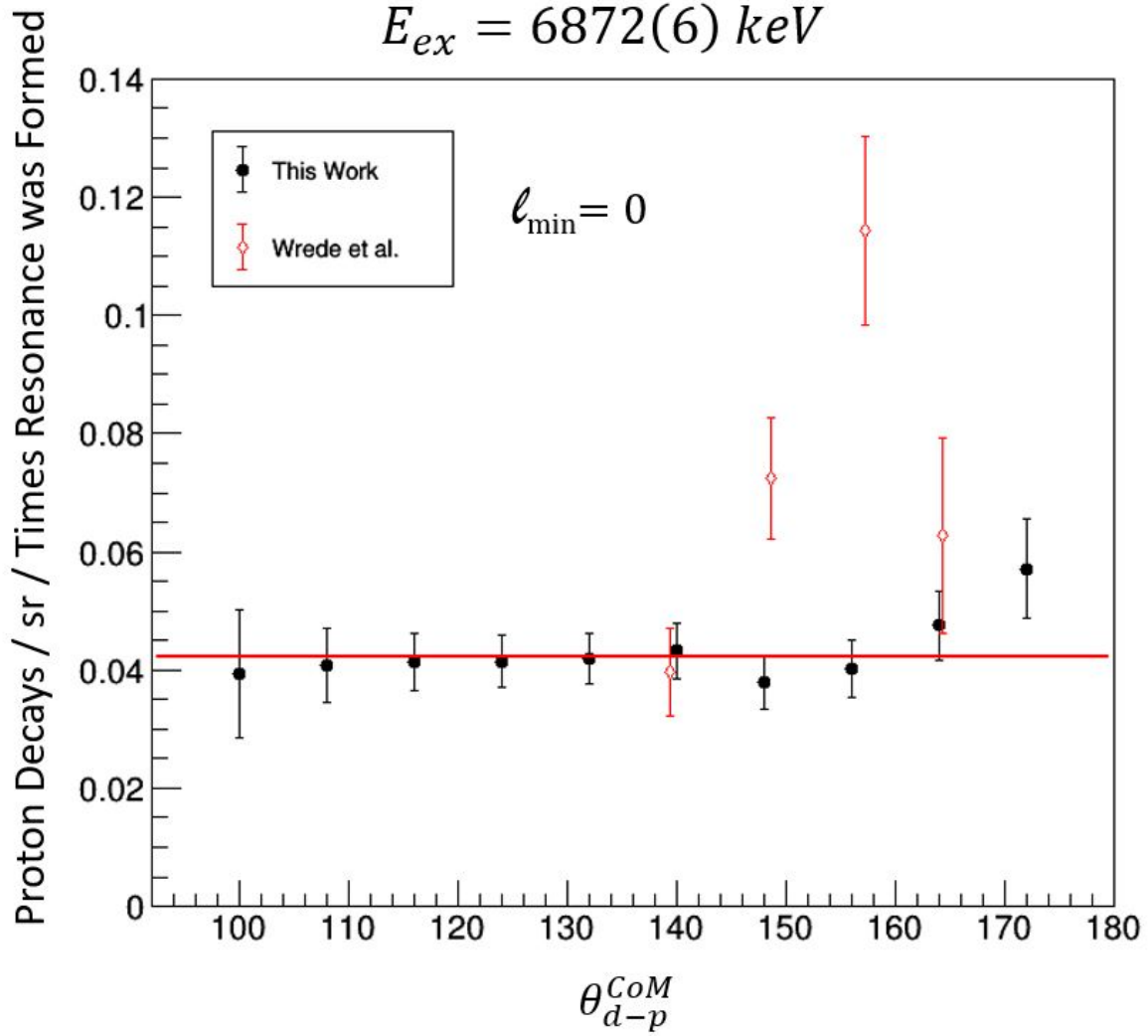


Figure 5.16: Deuteron decay-proton angular correlation for the 6872(6)-keV state p_0 branch. The solid black circles are the data from the current experiment and the open red diamonds are data from Wrede et al [4]. The solid red line is a fit to the current data using Equation 4.12 with only the $n = 0$ term included. Based on the satisfactory fit a minimum angular momentum transfer of $\ell_{\min} = 0$ is assigned to this decay.

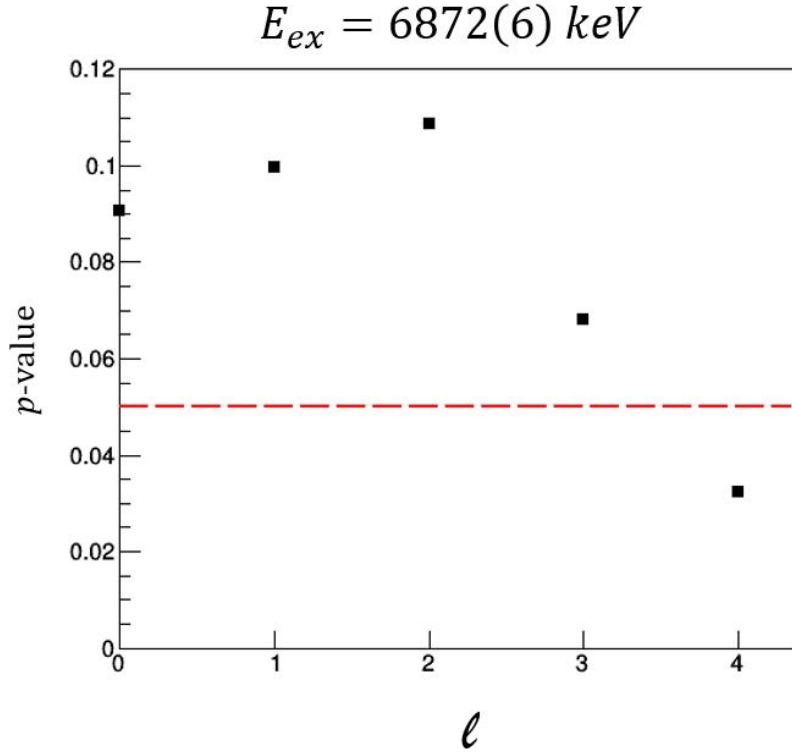


Figure 5.17: The statistical p -value from the fits of Equation 4.12 to the deuteron decay-proton angular correlation plotted versus the angular momentum transfer of the proton decay included in the fit for the p_0 branch of the 6872(6)-keV state. The red dashed line corresponds to a p -value of 0.05 which was the cutoff for accepting the fit. The $l = 0$ transfer was found to pass the test and therefore a minimum angular momentum transfer of $l_{min} = 0$ is assigned to this decay. The observed drop in p -value for $l = 3$ and $l = 4$ is due to the isotropic nature of the data and therefore fit is over-constrained after the addition of more free parameters.

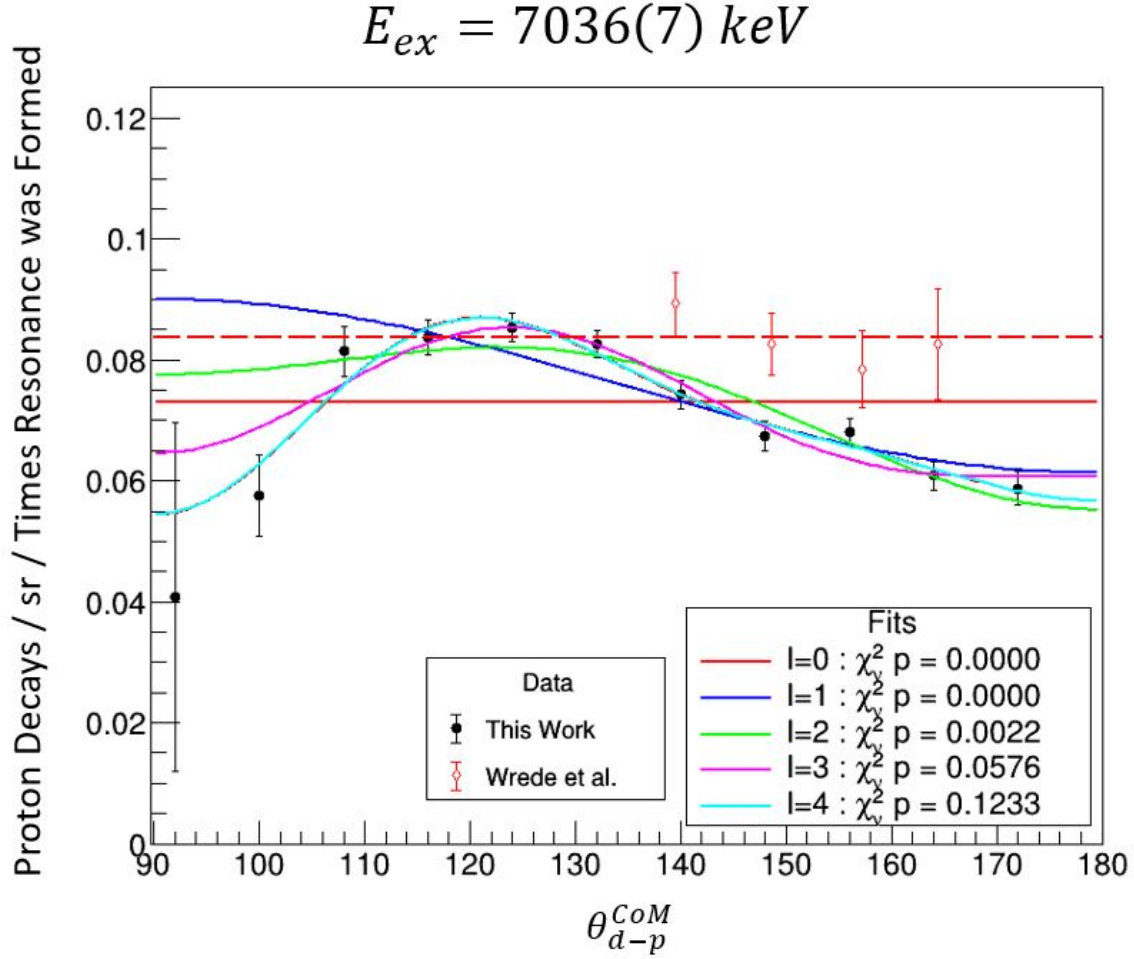


Figure 5.18: Deuteron decay-proton angular correlation for the 7036(7)-keV state p_0 branch. The solid black circles are the data from the current experiment and the open red diamonds are data from Wrede et al [4]. The solid lines are fits to the current data using Equation 4.12 with the l of the fit indicated by the different colors as shown in the legend. The red dotted line is the $l_{min} = 0$ fit Wrede et al assigned in their analysis. Based on the p -values test, a minimum angular momentum transfer of $l_{min} = 3$ is assigned to this decay in the present analysis.

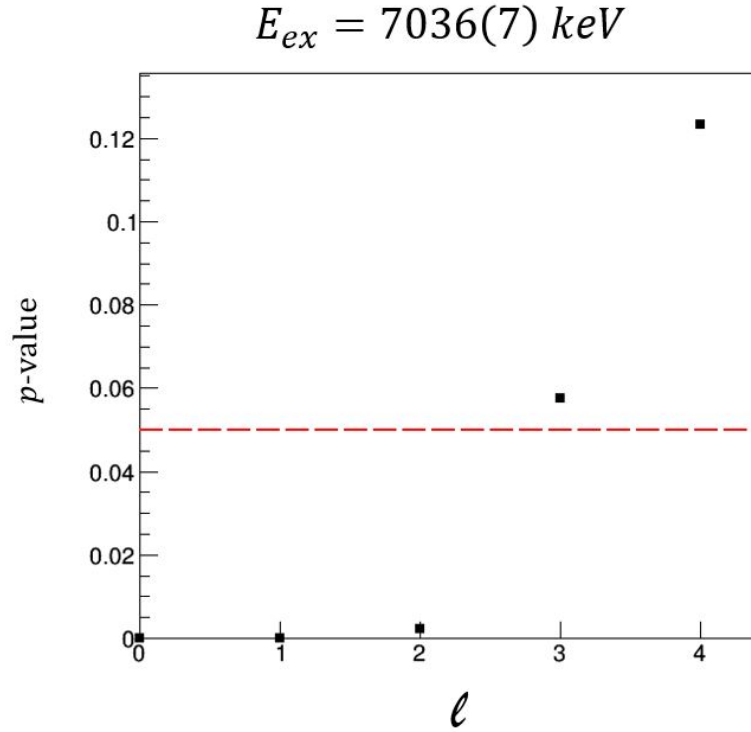


Figure 5.19: The statistical p -value from the fits of Equation 4.12 to the deuteron decay-proton angular correlation plotted versus the angular momentum transfer of the proton decay included in the fit for the p_0 branch of the 7036(7)-keV state. The red dashed line corresponds to a p -value of 0.05 which was the cutoff for accepting the fit. A large jump in p -value is seen between $l = 2$ and $l = 3$, with $l = 3$ being the first fit that passed the statistical test described in Chapter 4. Therefore, a minimum angular momentum transfer of $l_{min} = 3$ is the value taken for this state.

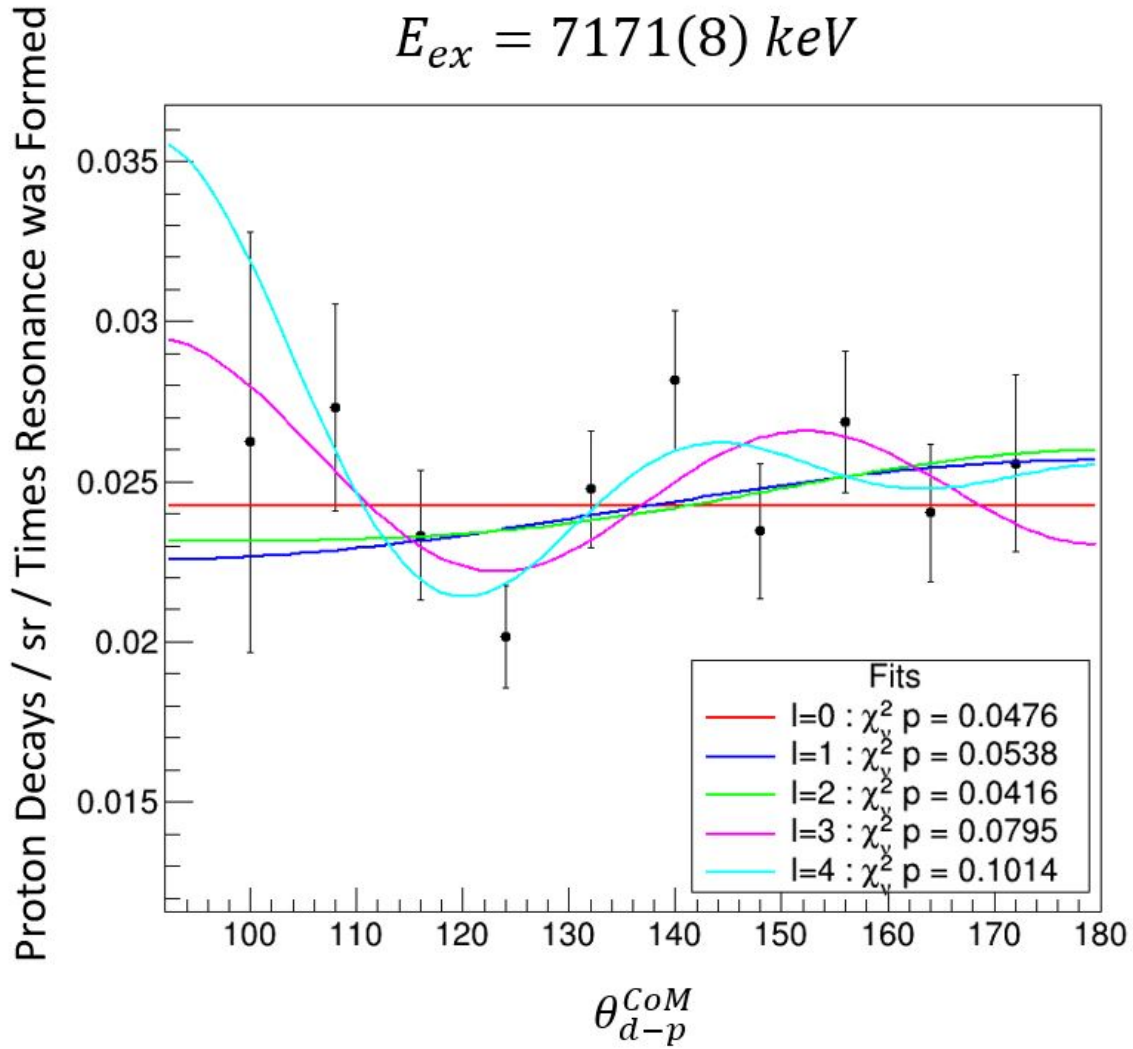


Figure 5.20: Deuteron decay-proton angular correlation for the 7171(8)-keV state p_0 branch. The solid lines are fits to the current data using Equation 4.12 with the l of the fit indicated by the different colors as shown in the legend. The $l = 1$ fit passed the p -value test and therefore we assign an $l_{min} = 1$ for this decay.

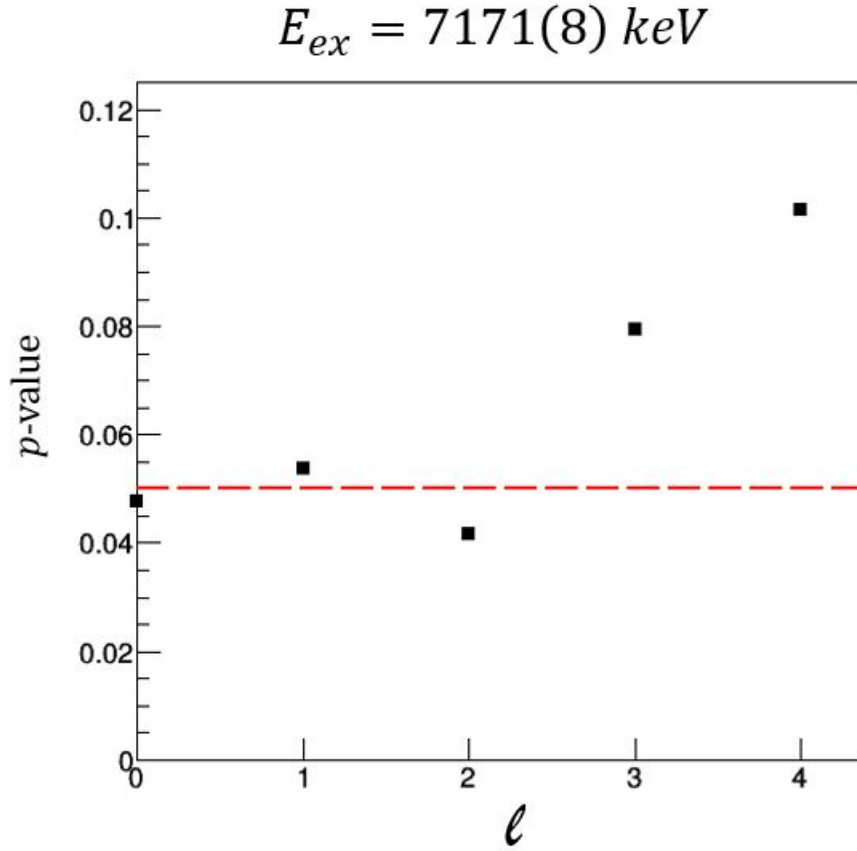


Figure 5.21: The statistical p -value from the fits of Equation 4.12 to the deuteron decay-proton angular correlation plotted versus the angular momentum transfer of the proton decay included in the fit for the p_0 branch of the 7171(8)-keV state. The red dashed line corresponds to a p -value of 0.05 which was the cutoff for accepting the fit. The $l = 1$ fit passed the p -value test and therefore we assign an $l_{min} = 1$ for this decay.

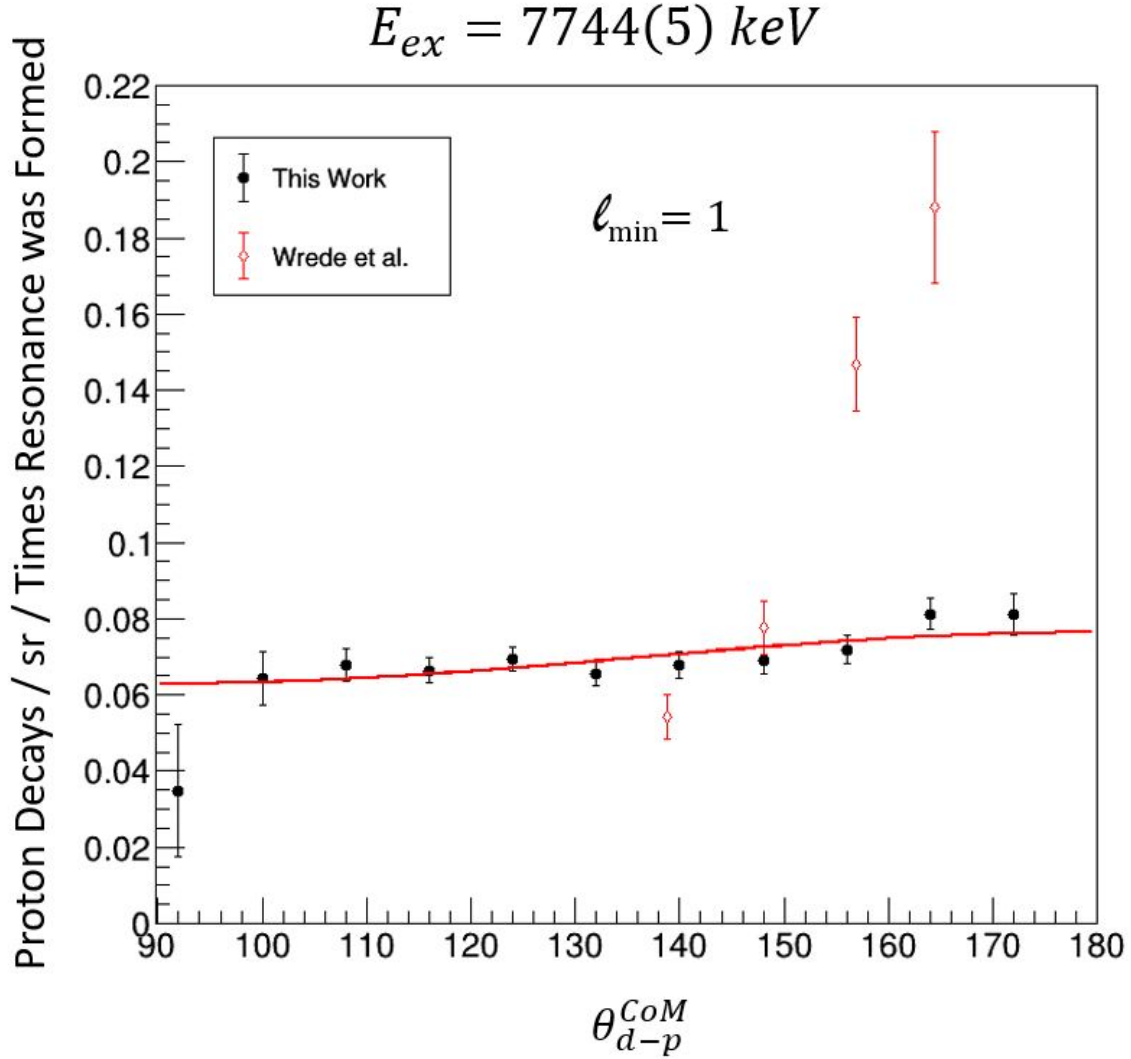


Figure 5.22: Deuteron decay-proton angular correlation for the 7744(5)-keV state p_0 branch. The solid black circles are the data from the current experiment and the open red diamonds are data from Wrede et al [4]. The solid red line is a fit using Equation 4.12 for an $l = 1$ decay, which was the first fit to pass the p -value test. This state is therefore assigned an $l_{\min} = 1$.

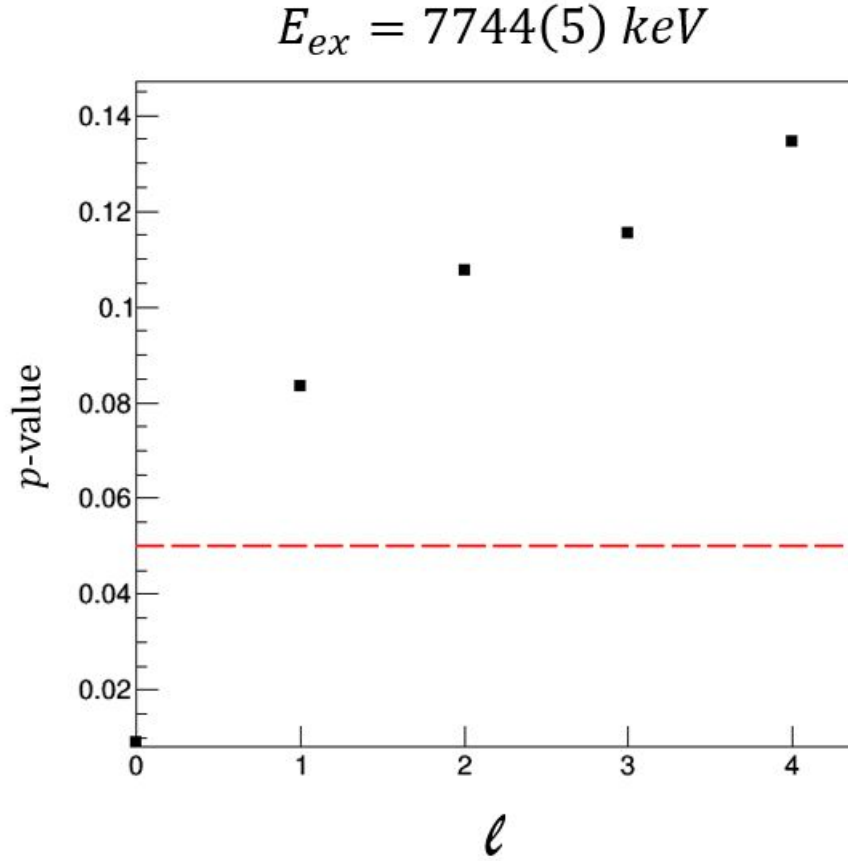


Figure 5.23: The statistical p -value from the fits of Equation 4.12 to the deuteron decay-proton angular correlation plotted versus the angular momentum transfer of the proton decay included in the fit for the p_0 branch of the 7744(5)-keV state. The red dashed line corresponds to a p -value of 0.05 which was the cutoff for accepting the fit. The first fit to pass the test was the $l = 1$ fit. In addition, a large jump is seen between the $l = 0$ and $l = 1$ fits, further confirming the assignment of $l_{min} = 1$.

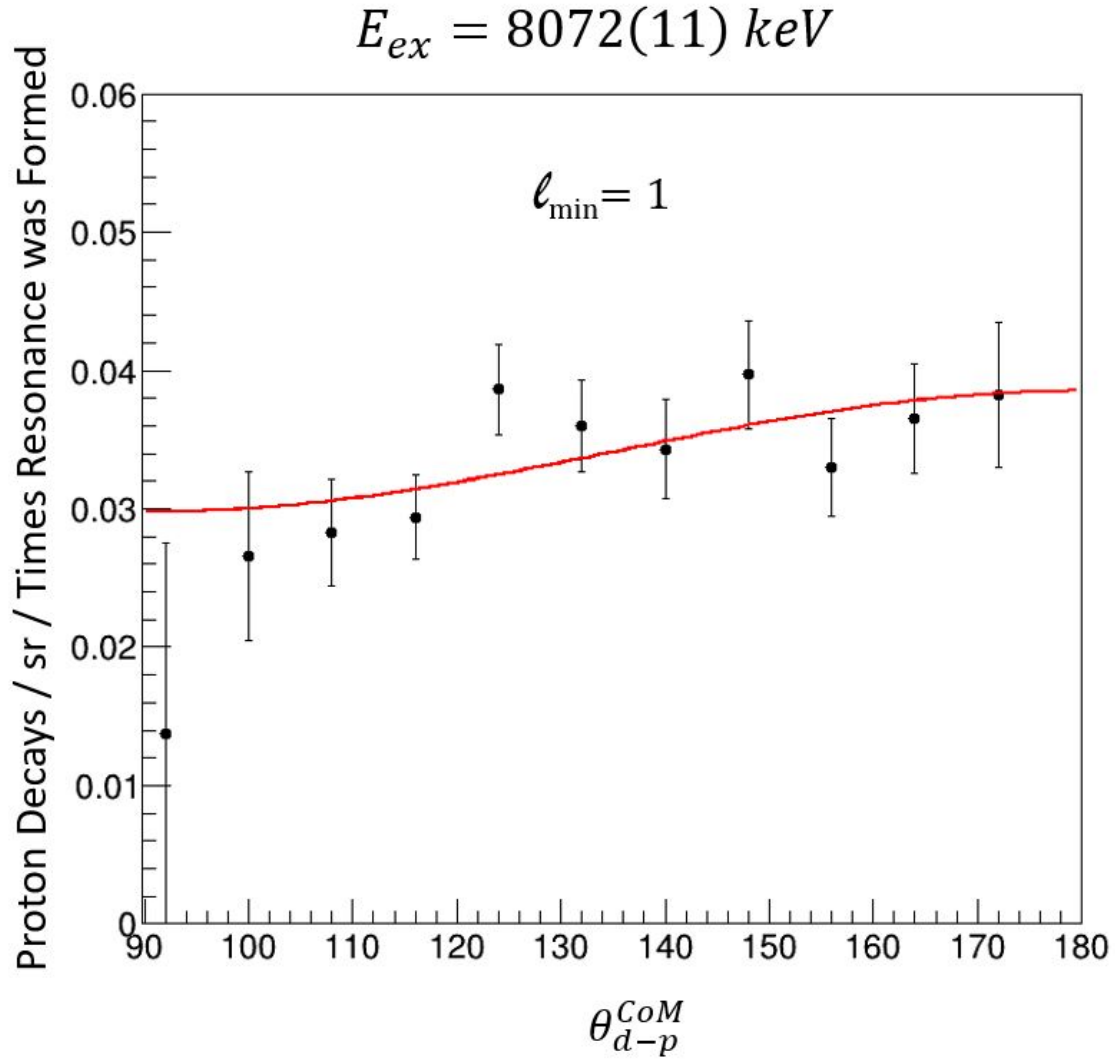


Figure 5.24: Deuteron decay-proton angular correlation for the 8071(11)-keV state p_0 branch. The solid red line is a fit using Equation 4.12 for an $l = 1$ decay. The $l = 0$ fit was close to passing the p -value test but the large jump between $l = 0$ and $l = 1$ was taken to be strong evidence that $\ell_{\min} = 1$ is the correct assignment.

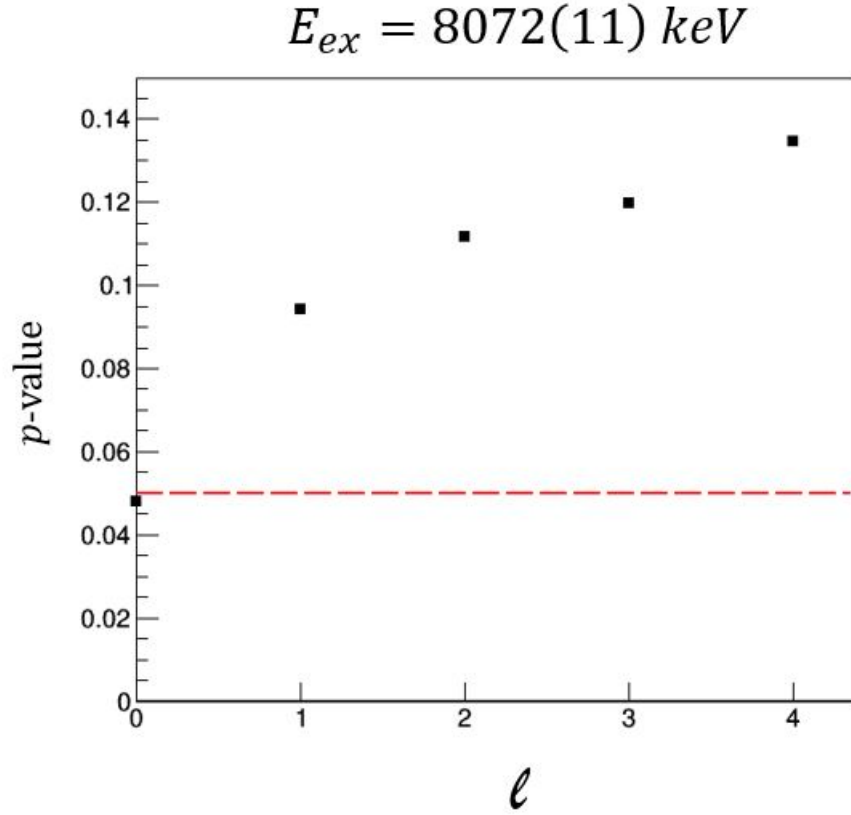


Figure 5.25: The statistical p -value from the fits of Equation 4.12 to the deuteron decay-proton angular correlation plotted versus the angular momentum transfer of the proton decay included in the fit for the p_0 branch of the 8071(11)-keV state. The red dashed line corresponds to p -value of 0.05 which was taken to be cutoff for accepting the fit. The $l = 0$ fit was close to passing the p -value test but the large jump between $l = 0$ and $l = 1$ was taken to be strong evidence that $l_{min} = 1$ is the correct assignment.

5.4 Discussion

In this experiment, many states in ^{31}S were populated. In the deuteron singles spectrum found in Figure 5.3, states with excitation energies ranging from the ground state to ~ 10 MeV are observed in ^{31}S . For constraining the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate, at classical nova temperatures, only states within ~ 1 MeV of the proton separation energy in ^{31}S will be important. Therefore, the discussion below only focuses on states observed in, and slightly above, this region.

5.4.1 The 6255 keV State

A γ -ray transition with $E_\gamma = 6254.4(16)$ keV was observed in coincidence with ^{31}S excitation energy ~ 6250 keV. This γ -ray is a transition directly to the ground state in ^{31}S . Comparison with previous literature [55] shows that a state with $E_{ex} = 6255.0(6)$ keV exists in ^{31}S . The deuteron peak corresponding to the population of this state falls in the region of the peak from the $^{12}\text{C}(p, d)^{11}\text{C}^*(2000.0)$ keV reaction, which is about an order of magnitude stronger than the peak of interest. In addition, a peak from the $^{16}\text{O}(p, d)^{15}\text{O}$ reaction to the 5240.9 keV state in ^{15}O is present. The presence of these two background peaks, with one being so intense, made the fit to the deuteron peak corresponding to this state unreliable and therefore no absolute branching ratio is reported. In a previous experiment [55], the state was observed to have an 80(10)% branch to the ground state via the $E_\gamma = 6254.3(6)$ -keV transition and two weaker γ -decay branches with $E_\gamma = 4020.2(5)$ keV and $E_\gamma = 2970.9(4)$ keV and branching ratios of 9.7(13)% and 10.1(14)% respectively. The peak at $E_\gamma = 6254.4(16)$ keV was observed to have 101 counts in this experiment. Taking into account the energy dependence of the efficiency of the array, and assuming the branching ratios from [55] are correct, we would expect to measure ~ 25 counts in the $E_\gamma = 4020.2(5)$ -keV peak and ~ 35 counts in the $E_\gamma = 2970.9(4)$ -keV peak. These are just below the limit for detection for a γ -ray peak in the current experimental setup due to signal-to-background ratios. Our observation is therefore consistent with the previously reported branching ratios. No proton decays were observed from this state. Due to the fact that this state is very close to the proton separation energy, it is likely that its dominant decay mode is γ -ray de-excitation because

proton emission is inhibited by the small probability of tunneling through the Coulomb barrier. However, the proton-decay Q-value for this state is 124 keV and therefore protons emitted from this state would have had energies between 60 and 180 keV in the laboratory frame in the current experiment. These energies are below the threshold for detection in the setup used.

5.4.2 The 6872 keV State

A state in ^{31}S at $E_{ex} = 6872(6)$ keV was observed in this work. The state was populated weakly compared to other states in the region, making the background subtraction of the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction to the 2000.0 keV state in ^{11}C difficult for the angle at which the two peaks overlapped. Therefore, the error assigned to the lower limit of the branching ratio is relatively large. The deuteron angular distribution for this state was only able to be measured at angles $20^\circ - 38^\circ$ due to the strong background peak. At these angles, the deuteron angular distribution, shown in Figure 5.7, agrees with a combination of DWBA calculations for $l = 0$ and $l = 2$ transfer. The black curve in Figure 5.7 represents an assumption of 50% contribution of an $l = 0$ and $l = 2$ component to the angular distribution. While the population of two distinct states can not be ruled out, the non-observation of states with similar excitation energies in previous experiments supports the conclusion that a single state is observed in this work. Based on this conclusion, we constrain the spin and parity of this state to $J^\pi = 1/2^+, 3/2^+, 5/2^+$. A branching ratio of $\Gamma_{p0}/\Gamma = 0.53^{+0.05}_{-0.17}$ was measured. In the measurement of the $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ reaction performed by Wrede et al [4], a state with $E_{ex} = 6872(2)$ keV and a proton-decay branching ratio of $\Gamma_{p0}/\Gamma = 0.37^{+0.09}_{-0.13}$ was measured. Due to the agreement between this experiment and Wrede et al. in excitation energy and proton-decay branching ratio, this is most likely the same state. The proton-deuteron angular correlation measured in this experiment is consistent with $l_{min} = 0$ while the previous measurement of Wrede et al. measured $l_{min} = 1$. A comparison of the data can be found in Figure 5.16. The data points at $\theta_{d-p}^{CoM} = 140^\circ$ and $\theta_{d-p}^{CoM} = 165^\circ$ have good agreement between the two measurements. However, our measurement did not reproduce the spike in intensity between $\theta_{d-p}^{CoM} = 150^\circ$ and $\theta_{d-p}^{CoM} = 160^\circ$. This measurement indicates

that due to the assignment of $l_{min} = 0$, spin-parities of $J^\pi = 1/2^+, 3/2^+$ for this state can not be ruled out.

5.4.3 The 7036 keV State

A state in ^{31}S at $E_{ex} = 7036(7)$ keV was observed in this work. This state was observed to have a very strong proton-decay branch to the ground state of ^{30}P . A branching ratio of $\Gamma_{p_0}/\Gamma = 0.93^{+0.14}_{-0.10}$ was measured. The deuteron-proton angular correlation is shown in Figure 5.18 and was assigned an $l_{min} = 3$, which implies the state has spin-parity of $J^\pi = 7/2^-, 9/2^-, 9/2^+, 11/2^+$. Higher spins are possible, however they are unlikely due to the observation of a strong proton decay branch and the suppression of higher spin proton decays by the angular momentum barrier. The deuteron angular distribution, shown in Figure 5.8, was found to be in good agreement with two previous data sets and indicates an angular momentum transfer of $l = 2$. The transferred angular momentum in the reaction suggests a spin-parity assignment of $J^\pi = 3/2^+, 5/2^+$. While comparison with DWBA calculations is informative, DWBA does have limitations. The DWBA treats reactions as one-step processes, however, at higher excitation energies it is likely that the state was populated via multiple interactions, and therefore perfect agreement with DWBA should not be expected.

Davidson et al [56] measured the $^{29}\text{Si}(^3\text{He},n)^{31}\text{S}$ reaction and found a state at $E_{ex} = 7006(25)$ keV. The angular distribution for this state was strongly peaked at 0° , indicating an $l = 0$ transfer, and therefore was assigned a spin-parity of $J^\pi = 1/2^+$. In addition, shell model calculations predicted a state with a spin-parity of $J^\pi = 1/2^+$ and isospin $T = 3/2$ in this region of excitation energy. Finally, comparison with known states in the the mirror nucleus ^{31}P led Davidson et al to identify this state as isospin $T = 3/2$. The non-observation of this state in other experiments in which the population of a $T = 3/2$ state was isospin forbidden, due to the specific reaction employed, was taken as further evidence of the assignment.

In Ref. [57], Vernotte et al measured the $^{32}\text{S}(^3\text{He},\alpha)^{31}\text{S}$ reaction and did not observe the state at $E_{ex} = 7006(25)$ keV previously reported by [56]. This supports Davidson et al's $T = 3/2$ argument as the population of a $T = 3/2$ state is isospin forbidden in the $^{32}\text{S}(^3\text{He},\alpha)^{31}\text{S}$ reaction. Vernotte et al did observe a state at $E_{ex} = 7033(5)$ keV which was well matched to DWBA calculations for an $l = 2$ transfer and was therefore assigned a spin-parity of $J^\pi = 5/2^+$. A measurement performed by Ma et al. of the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction reported a state at $E_{ex} = 7044(6)$ keV with an angular distribution that strongly suggested an $l = 2$ transfer [13]. Ma et al assigned a spin-parity of $J^\pi = 5/2^+$ to this state and identified it as the same state Vernotte et al measured at $E_{ex} = 7033(5)$ keV.

Wrede et al report a state at $E_{ex} = 7035.4(20)$ keV with a proton-decay branch to the ground state of ^{30}P consistent with 100 %. The state is identified as being the $E_{ex} = 7006(25)$ -keV $J^\pi = 1/2^+$; $T = 3/2$ state measured in [56]. This assignment is based on the angular correlation not showing any sign of anisotropy, which indicates an $l = 0$ decay and therefore constrains the spin parity of the state to $J^\pi = 1/2^+, 3/2^+$. Therefore, Wrede et al rule out the possibility of this state being the $J^\pi = 5/2^+$ state observed in [57, 13]. Wrede et al then conclude that the $J^\pi = 5/2^+$ state exists, but is populated weakly in their measurement and the peak observed is dominated by the $E_{ex} = 7035.4(20)$ -keV state, which is the $J^\pi = 1/2^+$ and $T = 3/2$ reported by Davidson et al at $E_{ex} = 7006(25)$ keV.

The results from this experiment indicate that Wrede et al may have misidentified the state they observed at $E_{ex} = 7035.4(20)$ keV with a strong p_0 branch. In the present work, a state at $E_{ex} = 7036(7)$ keV with a strong p_0 branch was also observed. Figure 5.18 shows the angular correlation measured in the present work with that measured by Wrede et al overlayed. While the overall normalization does not agree, the shape of the distributions are in good agreement. From the information available to Wrede et al, it makes sense to infer that the angular correlation was isotropic and therefore the state was likely to have a spin-parity of $J^\pi = 1/2^+$. However, when the angular range is increased, it is clear that the angular correlation is anisotropic and therefore the decay can not be $l = 0$. In this work, we report an $l_{min} = 3$, meaning the decay is statistically incompatible with $l = 0, 1, 2$ and

therefore the spin-parity of the state is constrained to $J^\pi = 7/2^-, 9/2^-, 9/2^+, 11/2^+$. The large discrete jump in the p -value for the fit between $l = 2$ and $l = 3$ is strong evidence that an assignment of a minimum angular momentum transfer of $l_{min} = 3$ is correct.

We therefore conclude that the state that Wrede et al observed is most likely the state reported here at $E_{ex} = 7036(7)$ keV, due to the similar excitation energies, consistent proton-decay branching ratios, and good agreement between the shape of the angular correlations. This state does not have a spin-parity of $J^\pi = 1/2^+$, and therefore is not the $E_{ex} = 7006(25)$ keV, $T = 3/2$ state reported by Davidson et al. However, due to inconsistent results in constraining the J^π from the deuteron angular distribution and the deuteron decay-proton angular correlation the spin-parity of this state remains ambiguous and we place a constraint of $J^\pi = 3/2^+, 5/2^+, 7/2^-, 9/2^-, 9/2^+, 11/2^+$. An alternate interpretation, which can not be ruled out, is that this experiment populated two nearly degenerate states with $l = 2$ and $l = 3$ transfers. This would mean that the previously observed $J^\pi = 5/2^+$ state and a previously unobserved $J^\pi = 7/2^-, 9/2^-, 9/2^+, 11/2^+$ state are both present at $E_{ex} \approx 7036(7)$ keV and both have p_0 branching ratios of 100 %.

5.4.4 The 7171 keV State

A state in ^{31}S at $E_{ex} = 7171(8)$ keV was observed in this work. The peak in the deuteron spectrum corresponding to the population of this state appeared as a shoulder on the 7036(7) keV state making the extraction of intensities difficult. The deuteron angular distribution is shown in Figure 5.9. At $20^\circ - 35^\circ$ the deuteron angular distribution is well matched with the DWBA calculation for an $l = 2$ transfer. At these angles, the presence of a background peak from the $^{16}\text{O}(p, d)^{15}\text{O}$ reaction to the 6176.3(17)-keV state in the region of the 7036(7)-keV and 7171(8)-keV states means that the peaks are not resolved. The intensity of the background peak is constrained with a measurement of the angular distribution using the mylar target foil. The intensity of the 7036(7)-keV state and this state were allowed to vary at each angle. The angular distribution of the 7036(7)-keV state well reproduces two previous data sets and therefore the angular distribution of the 7171(8)-keV state can be considered reliable. The error bar for the cross section at each angle in the deuteron angular

distribution takes into account the error in the intensity of the background peak in addition to the error in the intensity of this peak.

This state was observed to have a proton-decay branch to the ground state of ^{30}P with a branching ratio of $\Gamma_{p0}/\Gamma = 0.30^{+0.09}_{-0.06}$. The deuteron decay-proton angular correlation is shown in Figure 5.20. The $l = 1$ fit passes the p -value test and therefore an $l_{min} = 1$ cannot be ruled out. Two states were observed in the region by Wrede et al., $E_{ex} = 7157(2)$ keV and $E_{ex} = 7196(2)$ keV with branching ratios of $\Gamma_{p0}/\Gamma = 1.04^{+0.11}_{-0.63}$ and $\Gamma_{p0}/\Gamma = 0.67^{+0.08}_{-0.12}$ respectively [4]. Figure 5.26 shows a comparison of the results from this experiment with the two levels in the region observed in Wrede et al [4]. The overall normalization is in poor agreement with both of the states Wrede et al observed. However, Wrede et al report a very large lower error bar on the branching ratio for the $E_{ex} = 7157(2)$ -keV state, which if taken to its limit would bring the overall normalization of the angular correlation close to what was measured in this experiment.

The possibility of this state being the same state as the 7196(2) keV state from Wrede et al is ruled out due to the 25 keV difference in excitation energy, which is more than a 3σ difference, and the poor agreement between the shape of the angular correlations. Therefore, we interpret this state as the same state as the $E_{ex} = 7157(2)$ keV state measured by Wrede et al as the excitation energies disagree by 14 keV, which is less than a 2σ difference. The p -value test yields $l_{min} = 1$ and the angular distribution is interpreted as being an $l = 2$ transfer. This constrains the spin-parity of the state to $J^\pi = 3/2^+, 5/2^+$.

5.4.5 The 7744 keV State

A state in ^{31}S at $E_{ex} = 7744(5)$ keV was observed in this work. This state was observed to have a proton-decay branch to the ground state of ^{30}P with a branching ratio of $\Gamma_{p0}/\Gamma = 0.88^{+0.08}_{-0.04}$. The deuteron decay-proton angular correlation is shown in Figure 5.22 and resulted in an assignment of $l_{min} = 1$. Wrede et al observed a state at $E_{ex} = 7744(3)$ keV, which had a p_0 branching ratio of $\Gamma_{p0}/\Gamma = 1.0^{+0.06}_{-0.06}$ and was assigned an $l_{min} = 2$. The angular correlations measured in this experiment strongly disagree with Wrede et al and

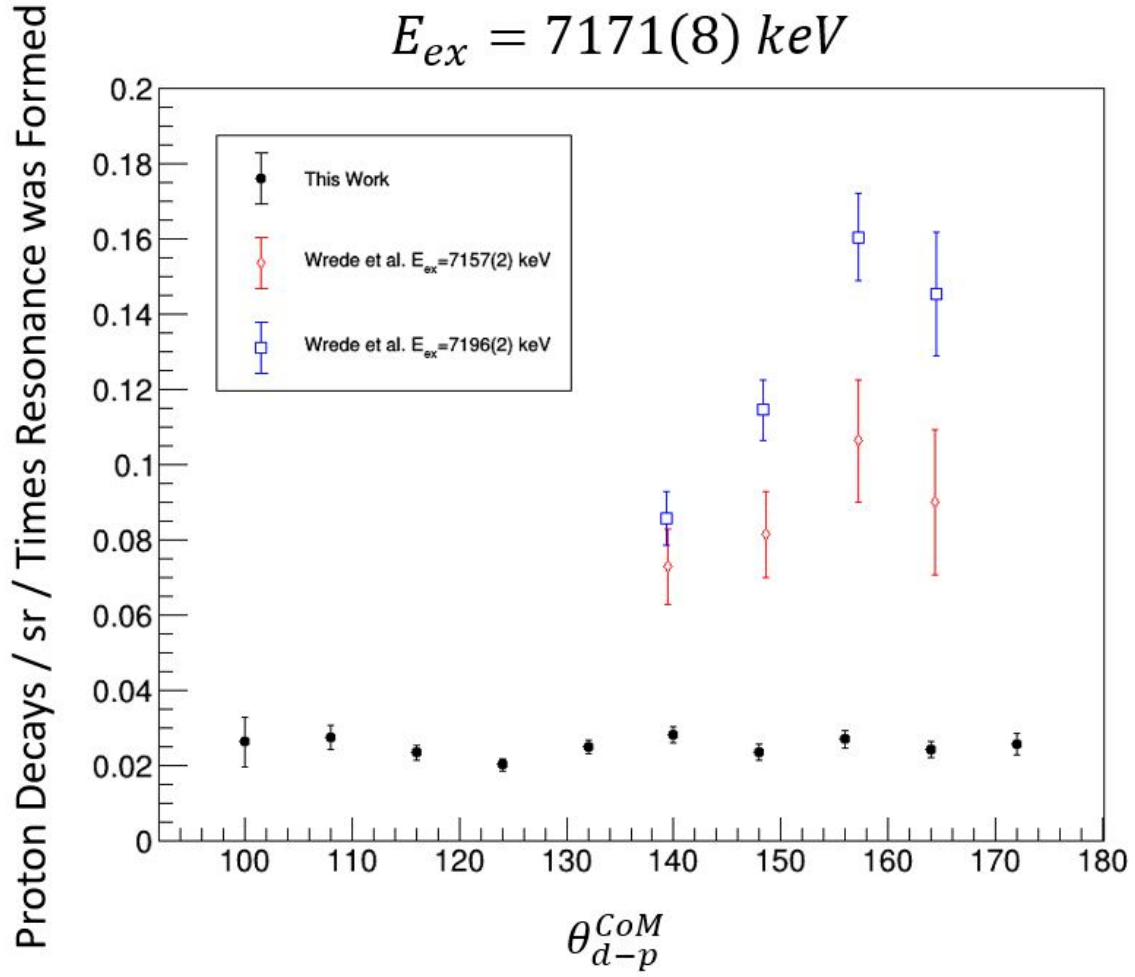


Figure 5.26: Deuteron decay-proton angular correlation for states in the region of the $E_{ex} = 7171(8)$ -keV state. The black circles are the results from the p_0 branch of the 7171(8) keV state from this experiment. The open diamonds and open squares are results from two states at 7156(2) keV and 7196(2) keV respectively, measured by Wrede et al. [4]

therefore the state populated in this experiment is likely not the same state observed by Wrede et al. Based on the assignment of l_{min} , we constrain the spin-parity of this state to $J^\pi = 1/2^-, 3/2^-, 3/2^+, 5/2^+, 7/2^-, 9/2^-, 9/2^+, 11/2^+$. This state, along with the 7912(9)-keV and 8071(11)-keV states were not fully resolved in the deuteron spectrum and the angular distributions for all three states exhibited the same structure. Comparison to DWBA calculations did not yield a reliable assignment of the angular momentum transfer for these three states.

5.4.6 The 7912 keV State

A state in ^{31}S at $E_{ex} = 7912(9)$ keV was observed in this work. The region of the proton decay matrix where the p_0 branch from this state would be located had slightly more counts than background in neighboring regions, but no structure was observed that was similar to the other proton decays. There were not enough statistics to perform an angular correlation analysis. A 2D gate was drawn in the region where the decay was expected and from the number of counts in the gate, an upper limit on the branching ratio of $\Gamma_{p_0}/\Gamma < 0.23$ was extracted, assuming isotropy.

5.4.7 The 8071 keV State

A state in ^{31}S at $E_{ex} = 8071(11)$ keV was observed in this work. This state was observed to have a proton-decay branch to the ground state of ^{30}P with a branching ratio of $\Gamma_{p_0}/\Gamma = 0.42^{+0.08}_{-0.06}$. The deuteron-proton angular correlation was well fit with an angular correlation function of $l_{min} = 1$. Based on this assignment, spin-parities of $J^\pi = 1/2^+$ and $3/2^+$ are ruled out for this state.

Table 5.2: Comparison between previous measurements and the present work of the excitation energy and spin-parity of states in ^{31}S between 6800 keV and 8200 keV.

Davidson et al [56] ($^3\text{He}, n$)		Vernotte et al [57] ($^3\text{He}, \alpha$)		Ma et al [13] (p, d)		Wrede et al [4] ($^3\text{He}, t$)		Present Work (p, d)	
E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π
6835(25)	$1/2^+$	6966(5)	$1/2^+$	6848(9)	$11/2^-$	6836(2)	$(1/2^+ - 9/2^-)$	7036(7)	$(3/2^+ - 11/2^+)$
				6848(9)	$(3/2^-, 5/2^+)$				
6870(25)						6872(2)	$\geq 1/2^-$	6872(6)	$(1/2 - 5/2)^+$
6921(25)						6939(3)	$(1/2 - 5/2)^+$		
7006(25)						6961(3)	$(1/2^+)$		
7039(25)		7033(5)	$5/2^+$	7044(6)	$5/2^+$	7036(2)	$(1/2^+)$	[7036(7)] ^a	$(3/2^+ - 11/2^+)$
7112(25)									
7165(25)		7156(5)	$5/2^+$			7157(2)	$(3/2^-, 5/2^+)$	7171(8)	$(3/2, 5/2)^+$
7199(25)						7196(2)	$\geq 1/2^-$		
7310(25)						7301(3)	$11/2^+$		
7445(25)						7496(3)	$(1/2^+ - 11/2^+)$		
						7501(3)	$(1/2^+ - 13/2^-)$		
7522(25)				7510(6)		7519(3)	$(1/2^+ - 13/2^-)$		
7600(25)						7585(3)	$(1/2^+ - 13/2^-)$		
7660(25)						7641(3)	$(5/2^- - 13/2^-)$		
						7698(3)	$(5/2)^+$		
7730(25)		7725(5)		7728(4)		7723(3)	$1/2^-$		
						7744(3)	$(1/2^+ - 13/2^-)$		
(7768(25))						7774(3)	$(1/2^+ - 13/2^-)$	7744(5)	$\geq 1/2^-$

^aIt is possible the state observed here is the 7044(6)-keV state observed by Ma et al. However, we conclude that it is most likely the 7036(2)-keV state observed by Wrede et al.

Table 5.2 Continued

Davidson et al [56] ($^3\text{He}, n$)		Vernotte et al [57] ($^3\text{He}, \alpha$)		Ma et al [13] (p, d)		Wrede et al [4] ($^3\text{He}, t$)		Present Work (p, d)	
E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π	E_{ex} (keV)	J^π
7850(25) (7888(25))				7912(5)	$1/2^+$	7824(3) ($1/2^+ - 13/2^-$) 7859(3) ($1/2^+ - 13/2^-$) 7894(3) ($1/2, 3/2, 5/2$) ⁺ 7905(3) ($1/2^+ - 13/2^-$) 7932(3) ($1/2^+ - 13/2^-$) 7945(3) ($1/2^+ - 13/2^-$) 7973(3) ($1/2^+ - 13/2^-$) 8015(3) ($1/2, 3/2, 5/2$) ⁺ (8030(3)) ($1/2^+ - 13/2^-$) 8044(3) ($1/2 - 5/2$) ⁺		7912(9)	
7985(25)				8049(6) ($1/2 - 5/2$) ⁺ 8049(6) ($1/2 - 5/2$) ⁺		(8060(3)) 8071(3) ($1/2^+ - 13/2^-$) (8106(10)) ($1/2^+ - 13/2^-$) 8131(3) $\geq 1/2^-$ 8178(3) ($5/2^+ - 13/2^-$)		8071(11)	$(3/2^+ - 11/2^+)$
(8082(25))									
8183(25)				8171(12)					

Table 5.3: Comparison of measured Γ_{p_0}/Γ and l_{min} between the measurement by Wrede et al and the present work.

Wrede et al [4]			Present Work		
E_{ex} (keV)	l_{min}	Γ_{p_0}/Γ	E_{ex} (keV)	l_{min}	Γ_{p_0}/Γ
6872(2)	1	$0.37^{+0.09}_{-0.13}$	6872(6)	0	$0.53^{+0.05}_{-0.17}$
7036(2)	0	$1.05^{+0.05}_{-0.05}$	7036(7)	3	$0.93^{+0.14}_{-0.10}$
7157(2)	0	$1.04^{+0.11}_{-0.63}$	7171(8)	1	$0.30^{+0.09}_{-0.06}$
			7744(5)	1	$0.88^{+0.08}_{-0.04}$
7905(3)		$0.34^{+0.12}_{-0.29}$	7912(9)		≤ 0.23
8071(3)		$1.07^{+0.22}_{-0.75}$	8071(11)	1	$0.42^{+0.08}_{-0.06}$

Chapter 6

Conclusion

In conclusion, a single γ -ray transition from a state above the proton separation energy was observed. The measured energy of the γ -ray agrees well with previously reported values. The non-observation of other branches is consistent with the γ -ray transition having an 80 – 100% branching ratio. Many states above the proton separation energy were observed to have proton-decay branches. The p_0 branch was analyzed for the six lowest energy proton-emitting states observed in this work. The summary of the results from these states can be found in Table 6.1. In this chapter, the impact of these results on the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate is discussed. The challenges of the current measurement are described and a possible future measurement is proposed.

6.1 The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ Reaction Rate

For the evaluation of the reaction rate, only states with resonance energies $E_r < 1500$ keV were considered. This cutoff was made due to the very small contribution any state above this energy would have to the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate at classical nova temperatures. In addition, the 6255.0-keV state is not included as the current measurement did not offer any new information on the resonance parameters. In Figure 6.1, the reaction rates for the three proton-emitting states with $E_r < 1500$ keV measured in this work are shown. The bands represent the uncertainty in the rate due to the uncertainty in the spin-parity of the resonance. The parameters used for the calculation of these rates are listed in Table 6.2.

Table 6.1: Summary of results for observed proton-emitting states. In this table l_n is the transferred angular momentum in the reaction as inferred from comparison with DWBA calculations and l_{min} is the minimum angular momentum of the proton decay obtained from fits to the deuteron decay-proton angular distribution.

E_{ex} (keV)	E_r (keV)	l_n	l_{min}	J^π	Γ_{p0}/Γ
6872(6)	741.1	0 + 2	0	(1/2 ⁺ , 3/2 ⁺ , 5/2 ⁺)	0.53 ^{+0.05} _{-0.17}
7036(7)	905.1	2	3	(3/2 ⁺ , 5/2 ⁺ , 7/2 ⁻ , 9/2 ⁻ , 9/2 ⁺ , 11/2 ⁺)	0.93 ^{+0.14} _{-0.10}
7171(8)	1040.1	2	1	(3/2 ⁺ , 5/2 ⁺)	0.30 ^{+0.09} _{-0.06}
7744(5)	1613.1		1	$\geq 1/2^-$	0.88 ^{+0.08} _{-0.04}
7912(9)	1783.1				≤ 0.23
8071(11)	1942.1		1	(3/2 ⁺ , 5/2 ⁺ , 7/2 ⁻ , 9/2 ⁻ , 9/2 ⁺ , 11/2 ⁺)	0.42 ^{+0.08} _{-0.06}

To obtain values for Γ_γ the procedure explained in Reference [4] was used. States with $E_r \geq 979$ keV were assumed to have γ widths of $\Gamma_\gamma = 0.55$ eV based on known lifetimes of the 7214-keV and 7314-keV states in the mirror nucleus ^{31}P . States with $E_r \leq 676$ keV were assumed to have γ widths of $\Gamma_\gamma = 0.15$ eV based on the known lifetime of the 6909-keV state in ^{31}P . For states with $676 < E_r < 979$ keV, Γ_γ was linearly interpolated between these two values and rounded to the nearest 100 meV. While the assumption that Γ_γ varies linearly with excitation energy is a very crude approximation, in the absence of experimental values of Γ_γ for these resonant states it is a reasonable starting point.

The peak temperature of a classical nova is approximately 0.4 GK. In Figure 6.2, the rates for the three proton-emitting states with $E_r < 1500$ keV (solid bands) are compared with the reaction rates of low-lying resonances (dotted lines). The rates for the low-lying resonances are calculated using the parameters given in the recent work by Kankianen et al [14]. At classical nova temperatures the states observed in this work contribute minimally to the total $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate. The results of this experiment were not able to confirm or change the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate at classical nova temperatures. However, this experiment and analysis advanced the techniques for measuring proton emission from excited nuclear states

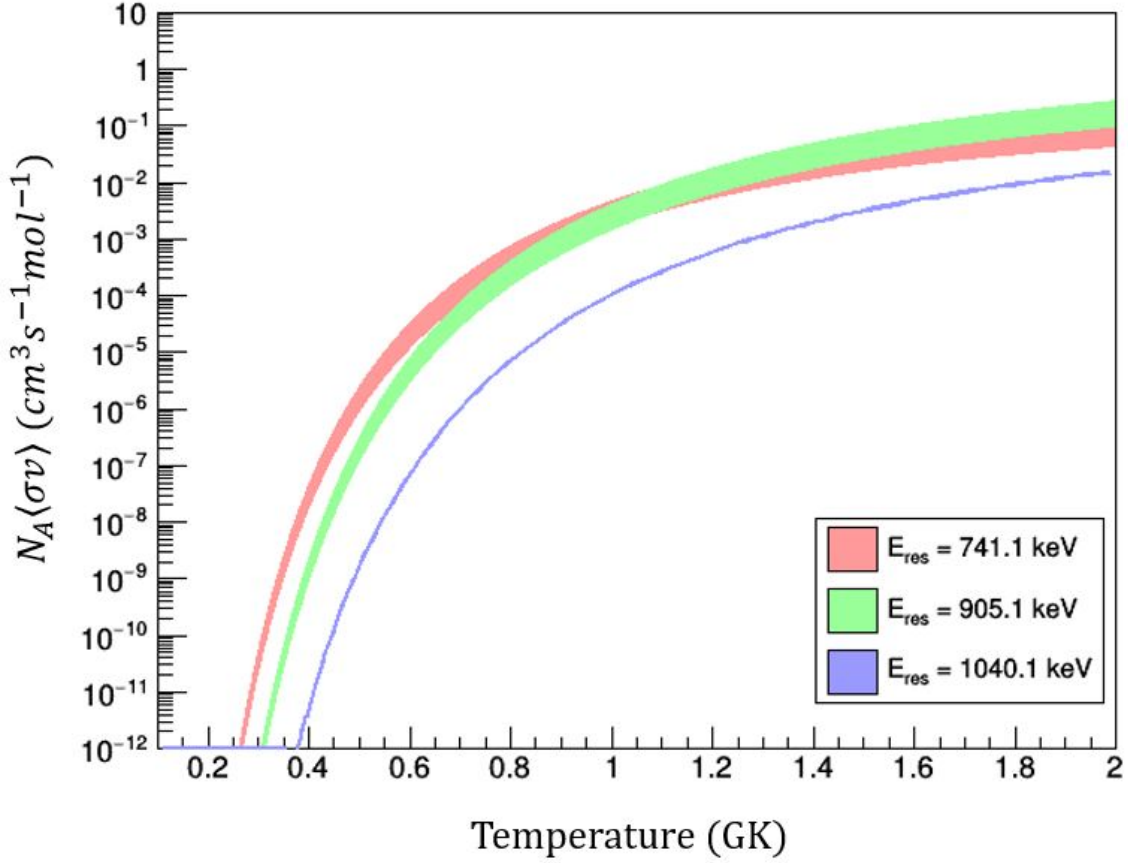


Figure 6.1: The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate for individual resonances as a function of temperature. The width of the bands represent the uncertainty due the angular momentum of the resonance. The resonance parameters used for this calculation can be found in Table 6.2.

Table 6.2: Resonant state parameters adopted for the calculation of the reaction rate. The values for Γ_γ have been adopted from Wrede et al. [4].

E_{ex} (keV)	E_r (keV)	J_r	Γ_{p0}/Γ	Γ_γ (keV)
6872(6)	741.1	(1/2 – 5/2)	$0.53^{+0.05}_{-0.17}$	3×10^{-4}
7036(7)	905.1	(3/2 – 11/2)	$0.93^{+0.14}_{-0.10}$	5×10^{-4}
7171(8)	1040.1	(3/2 – 5/2)	$0.30^{+0.09}_{-0.06}$	5×10^{-4}

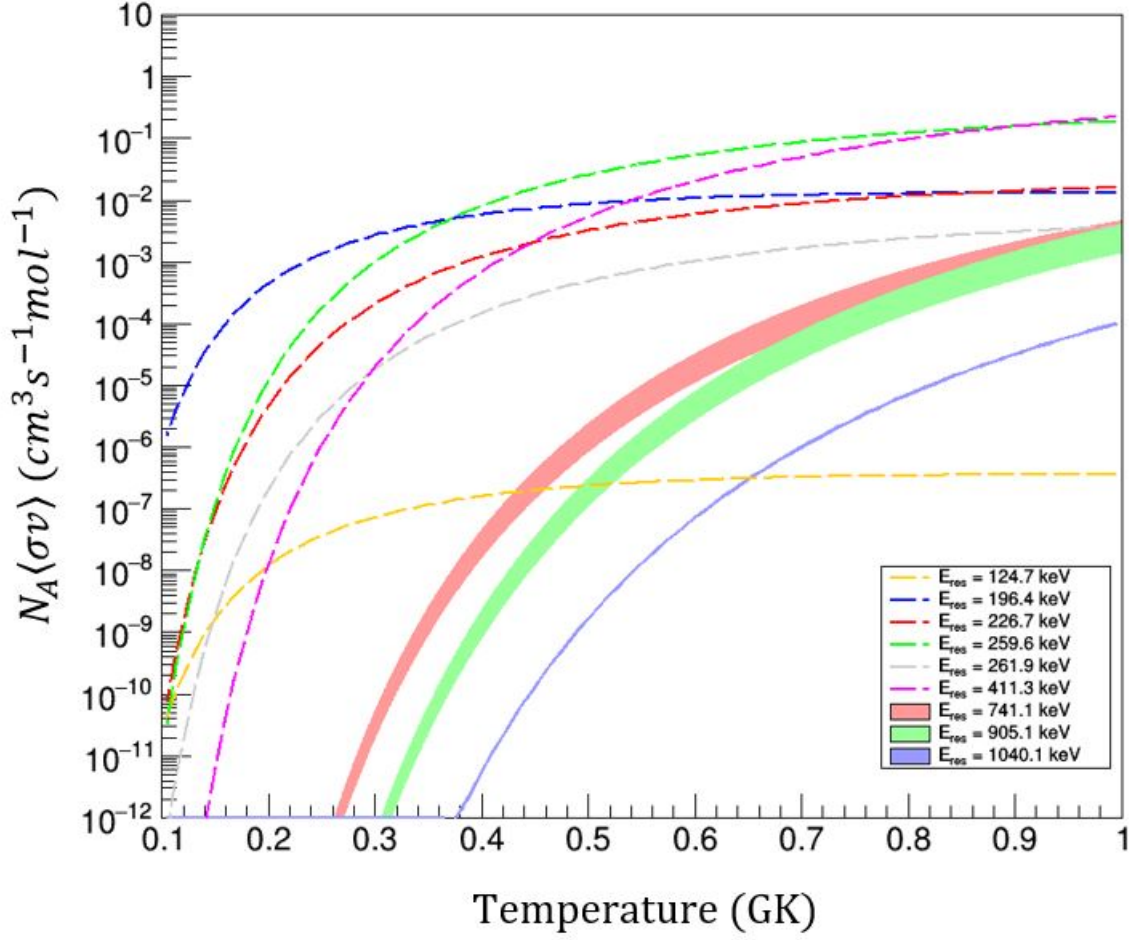


Figure 6.2: The $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rate for individual resonances as a function of temperature. In this figure, the different color bands are the results from the three proton-emitting states with $E_r < 1500$ keV that were observed in this experiment. The different dotted lines are the reaction rates of low-lying resonances that were reported in the recent work by Kankainen et al [14].

following a nuclear reaction. The challenges of this experiment and potential improvements are discussed in the next section.

6.2 Improvements And Future Work

In this section the challenges faced during the $^{32}\text{S}(p,d)^{31}\text{S}$ measurement are discussed and a new measurement with the potential to mitigate these challenges is proposed.

6.2.1 Target

The ZnS deposited on a carbon backing was not the ideal target for this measurement. There was significant background contribution from the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction in the region of interest for our measurement. In addition, due to the presence of water vapor, there was also background from the $^{16}\text{O}(p,d)^{15}\text{O}$ reaction in this region. The Q -values for (p,d) reactions on the stable zinc isotopes range from -8 to -9 MeV. The Q -value for the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction is -12.8 MeV, and therefore, at excitation energies above the proton separation energy in ^{31}S , the (p,d) reactions on the zinc isotopes were in the continuum and contributed a flat background. A future measurement could avoid issues with background contributions by making a different target and/or using a different reaction to populate states in ^{31}S . Choosing a target, or different reaction, such that the same reaction on contaminants in the target have a very different Q -value would eliminate the background features in the excitation energy region of interest that were present in this experiment. However, the selectivity of different reactions should be considered, as not all reactions will populate the same set of states.

6.2.2 Silicon Telescope

The S2 detectors used in the $^{32}\text{S}(p,d)^{31}\text{S}$ measurement were functioning properly, but due to the geometry of the setup, they were limited in angular resolution. The scattering chamber for the Hyperion array is very compact, with the HPGe clover detectors as close to the target as possible to maximize efficiency. This compactness requires that the silicon detectors be positioned very close to the target. Due to the finite size of the individual

segments on a silicon detector, moving closer to the target increases the angular range of each individual segment, limiting the angular resolution for detecting the ejectile of the reaction. Furthermore, the angular resolution and energy resolution are linked. The energy of the ejectile changes as a function of angle. Therefore, if an individual segment covers a larger angle it will suffer a loss in energy resolution. Lastly, the S2 detector is only capable of covering a small portion of angles, depending on the distance to the target. It would be desirable to sample a larger range of scattering angles. This would result in increased statistics and a larger range for the decay particle angular correlation measurement. A reaction measurement of this type would benefit greatly from a silicon telescope array with a higher solid angle and better angular and energy resolution.

6.2.3 Gamma-ray Detectors

Weak γ -ray branches are important for evaluating the reaction rate. Therefore, it is crucial to maximize γ -ray detection efficiency. During the $^{32}\text{S}(p,d)^{31}\text{S}$ measurement, a number of the HPGe clovers were not functioning properly so they could not be used in the data analysis. To ensure that a re-measurement is able to observe weak γ -ray branches, which may involve high energy γ -rays, a higher efficiency γ -ray detection array would help.

6.2.4 Upstream Detector

The upstream silicon detector was used to detect decay protons. Decay protons from low-lying resonances are emitted at low energies (100s of keV) making it necessary to have a particle detector that is sensitive to protons at low energies to detect them. It is difficult to measure charged particles with less than several hundred keV with even the best silicon detector setups due to noise. In the present work, no proton emitting states were observed with decay Q-values less than 700 keV. This is a combination of detection efficiency and physics. Lower-lying resonances are expected to have weaker proton-decay branches due to the decreased probability of penetrating the Coulomb barrier. However, in a previous measurement by Wrede et al [4], non-zero proton-decay branches from states with decay Q-values as low as 600 keV were observed.

6.3 Measuring The $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ Reaction with GODDESS

I propose a measurement of the properties of the resonant states in ^{31}S utilizing the $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ reaction and GODDESS (Gretina ORRUBA Dual Detectors for Experimental Structure Studies) (Oak Ridge Rutgers University Barrel Array) [58]. The $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ reaction has advantages over the $^{32}\text{S}(p,d)^{31}\text{S}$ reaction due to the ability to make a thin target that would not contribute to the background. A ^{31}P target could be made using elemental phosphorus deposited on a thin carbon backing. The Q-value for the $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ reaction is -5.4 MeV and the Q-values for the $^{12}\text{C}(^3\text{He},t)^{12}\text{N}$ and the $^{16}\text{O}(^3\text{He},t)^{16}\text{F}$ reactions are -17.4 MeV and -15.4 MeV respectively. The large difference in Q-values means that there would be no contribution from the $^{12}\text{C}(^3\text{He},t)^{12}\text{N}$ or the $^{16}\text{O}(^3\text{He},t)^{16}\text{F}$ reactions to the triton spectrum in the region of interest in ^{31}S excitation energy.

Gretina is the state-of-the-art γ -ray tracking array with a very high efficiency for detecting γ -rays due in part to the large volumes of HPGe that make up the detectors. Gretina tracks γ -rays, which provides a measurement of the position of interaction of a γ -ray within the HPGe crystal volume. Using γ -ray tracking eliminates the need for BGO shields, which can occupy a large portion of the solid angle and thereby decrease the geometric efficiency of the array. For comparison, Gretina has a γ -ray detection efficiency of 6.27(4)% at 1.3 MeV [59]. While the full Hyperion array in principle has a γ -ray detection efficiency of 3.0 % at 1.3 MeV, in the current measurement the efficiency was found to be 1.25 % at 1.3 MeV. Using Gretina could increase the γ -ray detection efficiency by a factor of 4.8 over what was achieved in the current measurement.

The GODDESS array consists of a large solid angle silicon array mounted inside the high efficiency γ -ray detector Gretina. The silicon array is a modified implementation of the Oak Ridge Rutgers University Barrel Array (ORRUBA). The silicon array consists of superX3 and QQQ5 detectors, all from Micron Semiconductor Ltd. The superX3 detectors are resistive strip detectors which form a barrel around the target position. The QQQ5 detectors are

annular detectors with segmentation in radius and azimuthal angle and are mounted as end-cap detectors at forward and backward angles. The total array covers $15^\circ - 165^\circ$ in polar angle with 1° angular resolution and $> 70\%$ azimuthal coverage [58]. For the proposed measurement, the entire forward barrel and the forward end-cap would consist of silicon telescopes. Due to the fact that this reaction is in normal kinematics, the tritons from the reaction will be emitted at forward angles and the silicon telescopes will be used for particle identification to select events in which a triton was detected in offline analysis. The decay protons will be detected at backward angles. The upstream barrel will consist of single superX3 detectors as low-energy decay protons will not penetrate a ΔE detector so PID is not possible. Decay protons will be identified by selecting events in the upstream barrel that came in coincidence with a triton detected at forward angles.

This configuration of silicon detectors will enable the detection of triton-proton coincidences with their relative angle covering the full range of almost $0^\circ - 180^\circ$. The added benefit of this large range of triton-proton angle is twofold. First, the angular correlation is symmetric about 90° in the angle between the triton and decay proton. This means that we will essentially measure the same information twice and will therefore increase our confidence in the final result. Second, this configuration will allow for the detection of triton-proton coincidences where the angle between the recoil and the decay proton is less than 90° . At small angles between the recoil and the decay proton, the decay proton will have an energy in the laboratory frame that is greater than the decay Q-value. This somewhat removes the limitation for measuring proton-decays of low-lying resonances due to the low proton energy. Using this setup it may be possible to measure proton decays from low-lying resonances that have not been previously observed.

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Appendices

A Solid Angle

In order to generate angular distributions it is important that the solid angle of each detector segment be well known. Therefore, at the end of the experiment, data were taken with an alpha source, of known activity, centered at the target location. These data were intended to be used to calculate the solid angle coverage of individual detector segments. However, due to the beam offset these data could no longer be used. Instead a source located at the target plane, but offset in the x and y directions, as measured using the method described in Appendix B, emitting particles isotropically in the lab frame was simulated. It was then possible to trace the trajectories of the particles and determine where they would have hit on the detector surface. Counting the number of particles that hit each individual segment, dividing by the total number released and finally multiplying by 4π results in the calculated solid angle of the segment. Solid angles for the individual segments were calculated in this way for use in generating angular distributions (see Figure A.1).

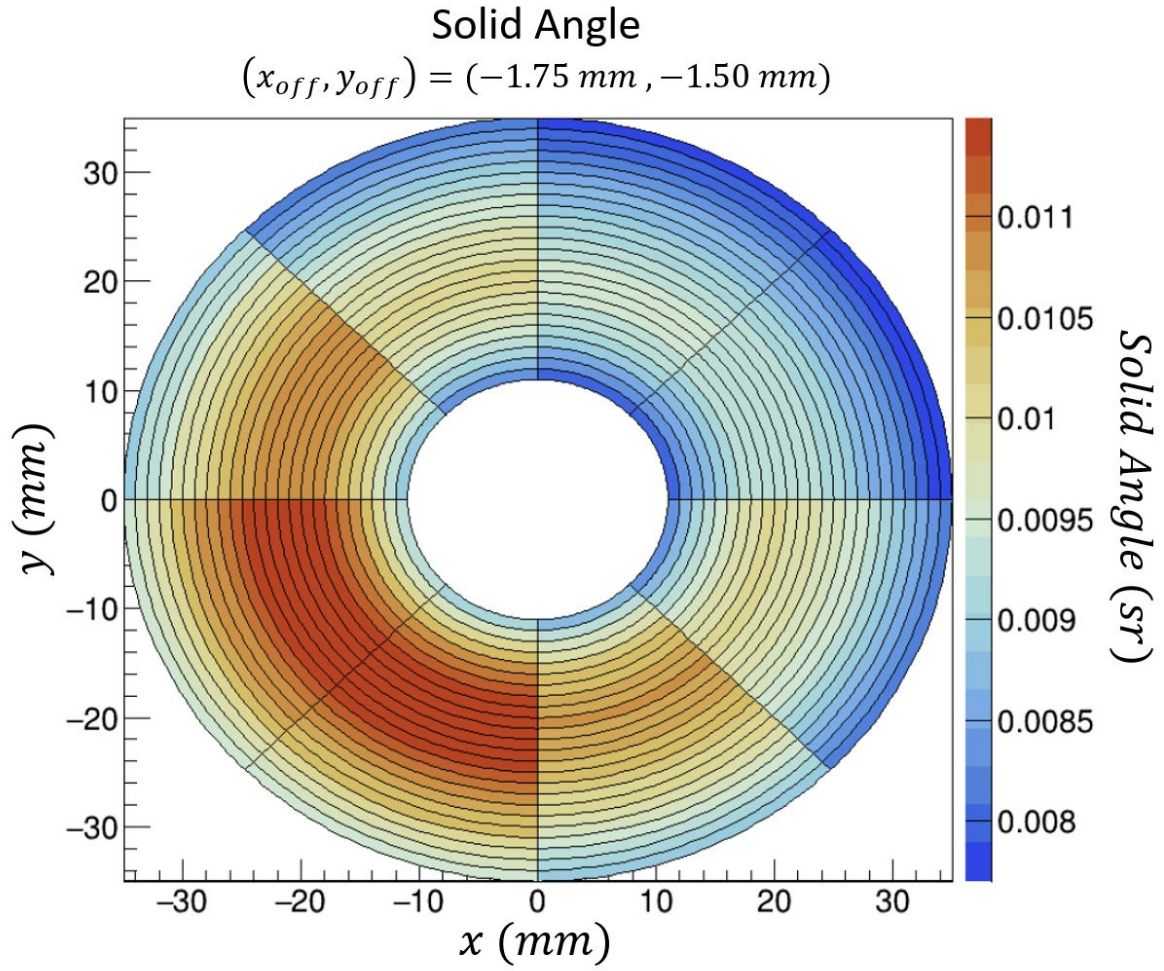


Figure A.1: Solid angle calculated for each detector segment by simulating an source, isotropically emitting particles, at the offset location.

B Beam Offset Correction

Throughout the experiment the beam was not centered with respect to the silicon detectors. At first order, one can take each ring of the detector to be at certain angle and if the beam were centered with respect to the detectors this would be true. However, with an off-center beam spot, the deuteron energy spectrum for a single ring will display peaks which are broadened due to the fact that these deuterons in fact had different scattering angles and therefore different energies. The beam was tuned using a phosphor target with a 1/4" (6.35 mm) diameter hole in the center (see Fig 3.9), which confined the beam offset within that dimension (± 3.175 mm from the center). However, due to the small distance between the detector and the target, beam offsets on the order of a couple millimeters have a significant effect and must be accounted for to maximize the resolution of excitation energy spectra.

To correct for this offset, an assumed offset was varied within ± 5 mm in the x and y directions where the nominal beam axis is taken to be the z-axis. At each offset value the deuteron energy spectrum from the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction, using the thin carbon foil target, was plotted. This resulted in a very clean deuteron energy spectrum in the region of the ground state transfer peak, as there were no other competing (p,d) reactions and the first excited state in ^{11}C is at 2.0 MeV. The resulting peak for the ground state transfer was fit with a gaussian function and the width was recorded (Fig B.2). Plotting the width of the peak as a function of the offset results in a smoothly varying surface (within the chosen step size of 0.1 mm) with a minimum at the value of the beam offset. When the $^{32}\text{S}(p,d)^{31}\text{S}$ data were then reanalyzed using the extracted offset it was found that the charged particle resolution was significantly improved.

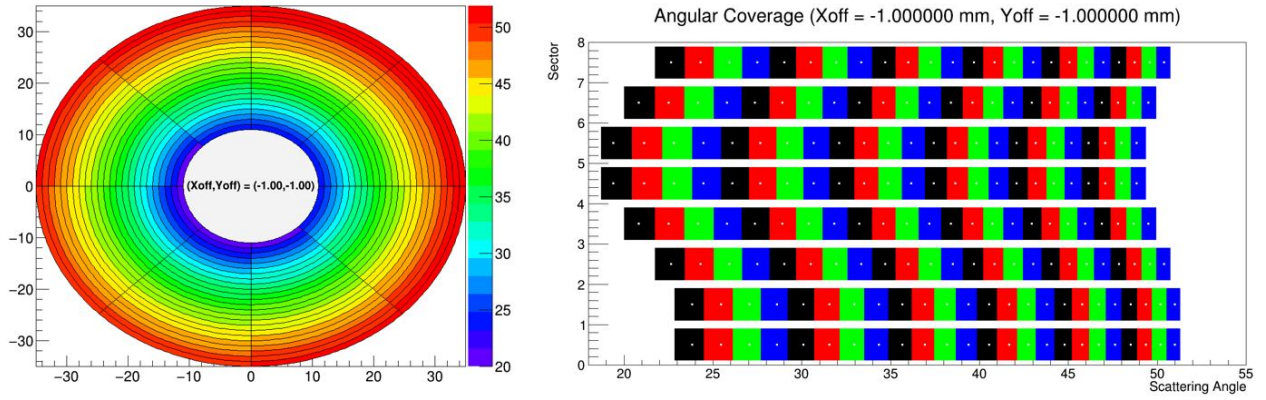


Figure B.1: Example of the effect of an offset of -1 mm in the x and y directions. Left: To scale face of the detector where the color of each segment represents the scattering angle of that segment's center point. Right: Angular coverage of each segment where the y-axis is the sector number and rings advance left to right by alternating colors.

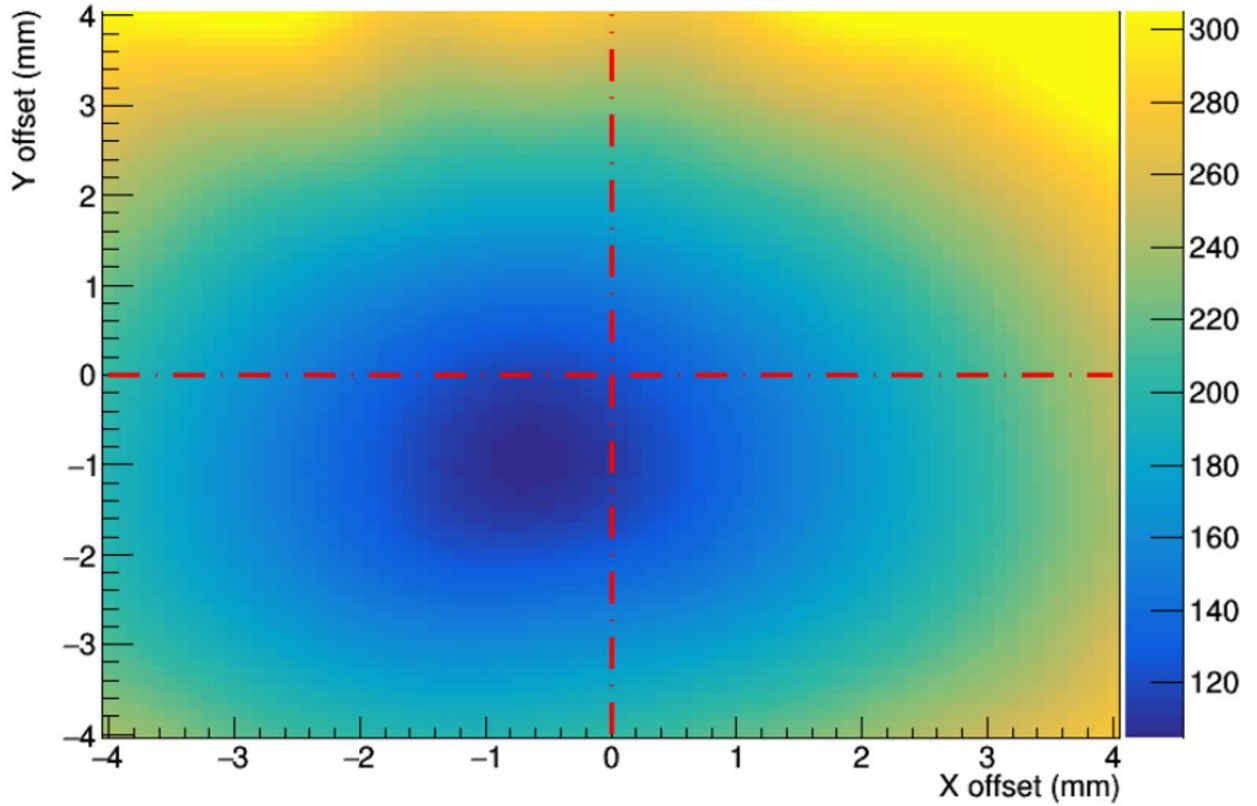


Figure B.2: The standard deviation about the $^{12}\text{C}(\text{p},\text{d})^{11}\text{C}$ ground state transfer peak. The red dotted lines mark the x and y axes.

C Derivation of Decay Kinematics

In this Appendix Equation 4.9 is derived from conservation of energy and linear momentum. Working in the laboratory frame with the z-axis aligned along the velocity of the recoil immediately following the reaction. The polar angle, θ is measured with respect to this axis. The naming convention used in Chapter 4 will be used here. Where the recoil nucleus is labeled with X , and the daughter and decay particle are labeled Y and b respectively. Conservation of energy

$$E_{initial} = E_{final} \quad (1)$$

The energy in the initial and final systems are the sum of the kinetic energy and masses of the nuclei present.

$$T_X + M_X c^2 = T_Y + T_b + M_Y c^2 + M_b c^2 \quad (2)$$

The Q-value for the decay is the difference between the initial and final masses of the nuclei.

$$Q = M_X - M_Y - M_b \quad (3)$$

Re-arrange Equation 4 with all of the mass terms on the left and kinetic energy terms on the right and substitute Equation 3 for the masses.

$$Q = T_Y + T_b - T_X \quad (4)$$

The conservation of linear momentum is split in to the longitudinal component (along the z-axis) and the transverse component (orthogonal to the z-axis). Conservation of longitudinal momentum,

$$p_X = p_b \cos \theta_b + p_Y \cos \theta_Y. \quad (5)$$

Conservation of transverse momentum,

$$0 = p_b \sin \theta_b - p_Y \sin \theta_Y. \quad (6)$$

Re-arrange Equation 5 such the term containing p_Y is isolated on the left, and square both sides.

$$p_Y^2 \cos^2 \theta_Y = (p_X - p_b \cos \theta_b)^2. \quad (7)$$

Re-arrange Equation 6 such the term containing p_Y is isolated on the left, and square both sides.

$$p_Y^2 \sin^2 \theta_Y = p_b^2 \sin^2 \theta_b. \quad (8)$$

Use the Pythagorean trigonometric identity to substitute the $\cos^2 \theta_Y$ in Equation 7 for $1 - \sin^2 \theta_Y$.

$$p_Y^2 (1 - \sin^2 \theta_Y) = (p_X - p_b \cos \theta_b)^2. \quad (9)$$

Next, divide Equation 9 by Equation 8.

$$\frac{p_Y^2 (1 - \sin^2 \theta_Y)}{p_Y^2 \sin^2 \theta_Y} = \frac{(p_X - p_b \cos \theta_b)^2}{p_b^2 \sin^2 \theta_b} \quad (10)$$

The p_Y terms cancel.

$$\frac{1}{\sin^2 \theta_Y} - 1 = \frac{(p_X - p_b \cos \theta_b)^2}{p_b^2 \sin^2 \theta_b} \quad (11)$$

Re-arrange Equation 11 and get an expression for $1/\sin^2 \theta_Y$ in terms of p_b, p_X , and θ_b

$$\frac{1}{\sin^2 \theta_Y} = \frac{(p_X - p_b \cos \theta_b)^2}{p_b^2 \sin^2 \theta_b} + 1 \quad (12)$$

Return to Equation 8 and re-arranging to isolate p_Y^2 on the left hand side.

$$p_Y^2 = p_b^2 \sin^2 \theta_b \left(\frac{1}{\sin^2 \theta_Y} \right) \quad (13)$$

Substitute $1/\sin^2 \theta_Y$ for the right hand side of Equation 12.

$$p_Y^2 = (p_X - p_b \cos \theta_b)^2 + p_b^2 \sin^2 \theta_b \quad (14)$$

$$p_Y^2 = p_X^2 - 2p_X p_b \cos \theta_b + p_b^2 \cos^2 \theta_b + p_b^2 \sin^2 \theta_b \quad (15)$$

$$p_Y^2 = p_X^2 + p_b^2 - 2p_X p_b \cos \theta_b \quad (16)$$

Express the momentum in terms of mass and kinetic energy using the relation $T = p^2/2m$.

$$2m_Y T_Y = 2m_X T_X + 2m_b T_b - 2\sqrt{2m_X T_X} \sqrt{2m_b T_b} \cos \theta_b \quad (17)$$

$$m_Y T_Y = m_X T_X + m_b T_b - 2\sqrt{m_X m_b T_X T_b} \cos \theta_b \quad (18)$$

Now use Equation 4 to substitute for T_Y

$$m_Y(Q - T_b + T_X) = m_X T_X + m_b T_b - 2\sqrt{m_X m_b T_X T_b} \cos \theta_b \quad (19)$$

Re-arrange and collect terms to get an expression for the Q-value of the decay.

$$Q = \frac{1}{m_Y} \left((m_X - m_Y)T_X + (m_Y + m_b)T_b - 2\sqrt{m_X m_b T_X T_b} \cos \theta_b \right) \quad (20)$$

The difference between the Q-value as calculated in Equation 20 and the ground state Q-value is the excitation energy of the state populated in the daughter (Y) of the decay. In the case of proton emission from an unbound state, the ground state decay Q-value is the difference between the excitation energy of the initial state in the parent (X) and the proton separation energy. This value is also the resonance energy E_r .

$$E_r = E_{ex,X} - S_p(X) \quad (21)$$

$$E_{ex,Y} = E_r - Q \quad (22)$$

$$E_{ex,Y} = E_r - \frac{1}{m_Y} \left((m_X - m_Y)T_X + (m_Y + m_b)T_b - 2\sqrt{m_X m_b T_X T_b} \cos \theta_b \right) \quad (23)$$

Equation 23 is the same as Equation 4.9, for the case where $X = {}^{31}\text{S}$, $Y = {}^{30}\text{P}$, and $b = p$.

Vita

Sean Burcher was born August 11, 1989 in New Jersey. He attended high school at Lenape High School in Medford, New Jersey, where he developed an interest in science and music. Sean went on to attend Rutgers University in New Brunswick, New Jersey, eventually graduating with a Bachelor of Science in Physics with a minor in Computer Science. During his time at Rutgers, Sean began doing research in nuclear physics and spent his summers at Oak Ridge National Laboratory. It was these experiences that led him to pursue a graduate degree in Physics. Sean moved to Tennessee full-time to attend the University of Tennessee, Knoxville for graduate school. He majored in Nuclear Astrophysics and successfully defended his dissertation in August 2019.