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I am submitting herewith a dissertation written by Dharmin D. Desai entitled "Electron Emission in Collisions of 0.5 MeV/u C^{2+} on H_2 ." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

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ELECTRON EMISSION IN COLLISIONS

OF 0.5 MeV/u C²⁺ ON H₂

A Dissertation

Presented for the

Doctor of Philosophy

Degree

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Dharmin D. Desai

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DEDICATION

This thesis is dedicated to my late grandfather

Mr. Thakorbhai Gulabbhai Desai

who instilled within me an appreciation for knowledge
and whose memory continues to inspire and encourage me.

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ABSTRACT

A new multi-spectrometer apparatus has been built and tested. It can be used to simultaneously measure the energy and angular distribution of electrons ejected between 0° and 8° with respect to the beam direction and to detect the recoil ions produced in ion-atom collisions. The multispectrometer apparatus consists of a 30° parallel plate electrostatic analyzer with a large position sensitive detector (PSD), a recoil ion time of flight (RITOF) spectrometer, and a charge state analyzer.

This work focuses on measuring the energy and angular distribution of electrons ejected between 0° and 8° with respect to the beam direction in coincidence with the recoil ion charge state and the exit charge state of the projectile ions in ionizing collisions between 0.5 MeV/u C^{2+} projectile and H_2 target. Electrons with kinetic energy between 0 eV and 1450 eV have been detected. Doubly differential cross sections have been obtained from the data. A prominent feature in the electron energy distribution is the binary encounter peak. The experimental binary encounter electron production cross sections are compared with theoretical results obtained using the impulse approximations.

Cusp electrons are nearly exclusively produced in collisions which involve single ionization of both projectile and target. Binary encounter electrons, on the other hand,

are produced in collisions in which the projectile remains intact and does not change charge. The only electrons which are ionized in the collisions are the binary encounter electrons themselves.

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CHAPTER 1

INTRODUCTION

Ionization of atoms and molecules produced in collisions with fast charged particles ($V_{\text{projectile}} \gg 1$ a.u.) plays an important role in such diverse fields as fusion energy, atmospheric and astrophysical sciences, and radiation biology (Toburen *et al* 1990).

In fast ion-atom collisions, many processes are possible, such as individual or simultaneous excitation and ionization of the electrons associated with either the target or the projectile. Target-electron transfer into bound or continuum states of the projectile is also possible. Often many of these processes are involved in the same ion-atom collision.

An ideal experiment would measure the initial and final momenta and charge states of projectile and target as well as the momenta of all ejected electrons and photons produced in the collision. Conservation laws would make some of the information redundant, which might serve as a check on the experiment. In an actual experiment only a limited amount of information is available. Practical constraints which limit the scope of an actual coincidence experiment include limited beam time, limited efficiency and resolution of the experimental apparatus, low target density, and small cross sections.

The focus of this thesis is the measurement of the production cross sections and the energy and angular distribution of electrons emitted between 0° and 8° with respect to the beam axis in coincidence with the target recoil ion charge states and the exit charge states of the projectile ions. A particular problem of such measurements is to extract a recoil ion from the interaction region without losing information about the momenta of free electrons produced together with a detected recoil ion. A multi-spectrometer apparatus has been designed to accomplish this. An electron energy analyzer is used to measure the energy and angular distributions of ejected electrons, and a time-of-flight analyzer is used to measure the charge state of the recoil ions. Exit charge states of the projectile ions are measured using a charge state analyzer which is also a part of the multispectrometer apparatus.

In our experiment, $0.5 \text{ MeV/u } \text{C}^{2+}$ projectile ions collide with H_2 target gas. We measure the energy and angular distribution of electrons ejected between 0° and 8° with respect to the beam direction with energies between 0 and 1450 eV. Our electron spectra reveal different regions associated with specific electron production mechanisms. We detect cusp electrons, Auger electrons, and binary encounter electrons. The cusp and the Auger electrons produce sharp features in the spectrum while the binary encounter electrons produce a broad structure-less peak. A sample spectrum is shown in Figure 1.1.

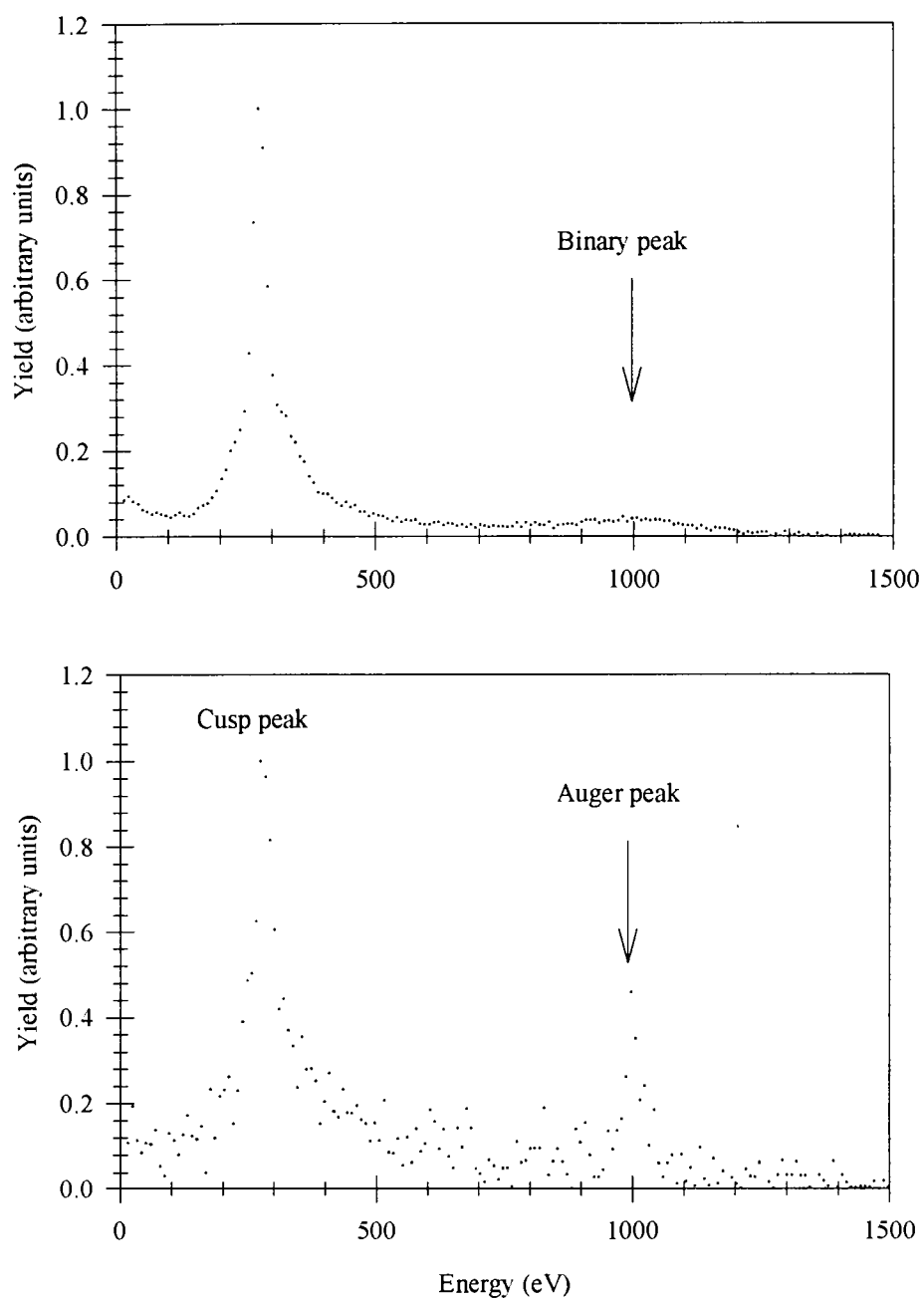


Figure 1.1 Electron yield in 0.5 MeV/u C^{2+} on H_2 collisions. The upper spectrum was measured without any coincidence requirements and clearly shows the cusp peak and the binary peak. The lower spectrum was measured in coincidence with exit charge state $4+$ of the projectile ion and shows the cusp and Auger peaks.

Electrons emitted near the forward direction in atomic collision processes are referred to as cusp electrons. The velocity of the ejected cusp electron is approximately equal to the velocity of the incident ion ($v_e = v_{ion}$). Cusp electrons were discovered independently in ion-atom (Crooks and Rudd 1970) and ion-foil collisions (Harrison and Lucas 1970) (Köver *et al* 1983). Cusp electrons in ion-atom collisions are a result of one of two different ionization mechanisms: electron loss to the continuum (ELC) and electron capture to the continuum (ECC).

The ELC process occurs when the projectile carries electrons into the collision (Breinig *et al* 1982). During an interaction with the target, projectile electrons can be excited to low lying projectile continuum states. The cusp electrons are then carried along with the beam. Thus, they are also sometimes referred to as convoy electrons. The ELC ionization process can be characterized as a “soft collision process” with a large impact parameter between target and projectile. It is also a low momentum transfer process, i.e. only a small momentum is imparted to the ejected electron. ELC electrons have almost zero energy in the projectile frame, and thus, in the laboratory frame, their velocity nearly equals the projectile velocity. The peak width at FWHM and the intensity of the ELC cusp are nearly independent of the projectile velocity (Köver *et al* 1983).

Electron loss to the continuum is a projectile ionization process. The interaction between the screened target nucleus and the projectile electrons generally dominates

this process. This interaction has been more thoroughly studied than the interaction between the target electrons and the projectile electrons which allows the target electrons to act as “quasi free” and obey kinematic conditions appropriate to the interaction of nearly free electrons with the projectile. Recently, however, the importance of the target electron - projectile electron interaction has been addressed by many investigators.

The electron - electron process has a threshold at an ion velocity approximately equal to the threshold electron velocity in the corresponding free electron ionization. However, this threshold is less precisely defined in ion - atom collisions because the target electrons are bound and therefore, have an initial momentum distribution rather than a well-defined momentum (Hülskötter *et al* 1991, Montenegro *et al* 1993, Wu *et al* 1994, Dörner *et al* 1994). Manson and Dubois demonstrate that, in some cases, ELC cross sections are completely dominated by electron - electron interaction processes (Manson and DuBois 1992). For neutral projectiles, the electron - electron interaction can dominate projectile ionization. It decreases in importance for more highly charged projectile ions, and for charged particle impact, is never more important than the electron - nucleus interaction.

The ECC process occurs when a bound target electron is captured into a low lying continuum state centered on the projectile ion. This is a likely process when the projectile is a proton or a more highly charged bare ion. The ECC peak width at

FWHM is proportional to the velocity of the projectile, but the intensity of this peak decreases with increasing projectile velocity because it becomes energetically less likely to occur (high momentum transfer) (Köver *et al* 1983). Even though the intensity of this peak falls rapidly at angles greater than zero, it does not vanish at any angles between 0° and 180° .

The cusp electrons detected in this experiment are almost exclusively ELC electrons since ELC is the dominant process for low charge state projectiles. This is also confirmed by measuring the exit charge states of the projectiles in coincidence with cusp electrons.

At approximately 1000 eV, a sharp peak is observed in our 0.5 MeV/u C^{2+} on H_2 electron energy spectra measured in coincidence with C^{4+} ions exiting the gas cell. This peak is due to the emission of projectile KLL Auger electrons (Deveney *et al* 1995). In fast ion-atom collisions, inner shell electrons of the target or the projectile ions can be excited or ionized. This leaves a vacancy in the inner shell which decays by the emission of photons or electrons. The electron ejection mechanism is known as the Auger effect. The Auger effect is the de-excitation of an excited atom by a non-radiative process. Pierre Auger first discovered this effect in 1925, thus the name “Auger electrons” (Auger 1925). It was later confirmed theoretically by Wentzel in 1927 (Wentzel 1927). The Auger effect is an auto-ionization process in which an inner shell vacancy is filled by an outer shell electron. The outer shell electron loses

energy in the transition, and energy is conserved through the ionization of another outer shell electron. The freed electron has a characteristic kinetic energy equal to the difference in energy between the initial and final configuration of the bound electrons. Since Auger electrons yield discrete structures in the energy spectrum, i.e. since they have characteristic energies, they are often used to study the composition of unknown surfaces, etc.

Binary encounter electrons (BEE) are ejected in the collision between a fast projectile ion and a semi-free outer-shell target electron. They constitute a prominent feature in the spectrum of the fast electrons ejected near the forward direction. In this spectrum, they form a broad peak. Because it is possible to understand this electron ejection mechanism by taking into account the interaction between only two members, a target electron and a projectile nucleus, they are called binary encounter electrons. The binary encounter electrons are produced when the target electron's potential becomes negligible compared to that of the projectile. Quasi-free target electrons, i.e. electrons residing in an outer shell, collide elastically with the projectile nucleus and are ionized into the continuum. In these collisions, the impact parameter between the projectile nucleus and the target electron is so small that it is often sufficient to consider only these two parameters for the description of the BEE's energy and angular distribution. This means that the shape of the screened Coulomb potential of the projectile is the most important parameter determining the distribution of these electrons in energy and emission angle (Kelbch *et al* 1992). Of course, the target electron is not really free but

bound, so the binding energy of that electron has to be taken into account in determining the energy of the binary encounter peak. It is $E_{BEE} = 4K_e \cos^2(\theta) - \varepsilon_i$ where K_e is the kinetic energy of the ejected electron whose velocity is the same as that of the projectile, θ is the laboratory detection angle, and ε_i is the binding energy provided by the target nucleus. The target nucleus is essentially reduced to providing an initial velocity distribution to the electron.

Binary encounter electrons ejected in ion-atom collisions provide important information about the Compton profile of the target electron, the scattering potential, the electronic stopping power of heavy ions, radiation damage in biological matter, etc. (Kelbch *et al* 1992).

There has been a considerable amount of interest in the investigation of the properties of binary encounter electrons, and many articles can be found in the current literature. Phenomena investigated theoretically, as well as experimentally, are the energy shift of the binary encounter peak (Lee *et al* 1990, Gonzalez *et al* 1993, Wolff *et al* 1993), the anomalous q^2 dependence of the doubly differential cross section (DDCS) (Richard *et al* 1990, Olson *et al* 1990, Reinhold *et al* 1990, Reinhold 1991a, Kelbch *et al* 1992, Zouros *et al* 1994), and structure in the energy and angular distribution of binary encounter electrons (Kelbch *et al* 1989, Kelbch *et al* 1992, Reinhold *et al* 1991b, Shinpaugh *et al* 1993).

Experimental studies involving the production of binary encounter electron emission as a function of the impact energy for U^{33+} on rare gas targets revealed “surprising structures” in the BEE energy spectrum at certain electron ejection angles (Kelbch *et al* 1989). Theoretical studies of ionizing collisions of “clothed” ions with atoms have explained the origin of these “surprising structures” (Reinhold *et al* 1991b). These studies show that these structures in the elastic differential cross section for the scattering of target electrons from the impinging ion are a result of interference, and that they are associated with the well-known phenomenon of rainbow scattering. The structure in the angular and energy emission pattern of binary encounter electrons appear only for the impact of very heavy ions; however, the influence of a screened potential is also visible for comparatively light ions (Jagutzki *et al* 1991).

As early as 1933, Bethe used the quantum-mechanical Born approximation to calculate cross sections for ion impact excitation and ionization of electrons bound in atomic orbitals (Bethe 1933). Classical calculations have also been used to model ion-atom collisions, like Gryzinsky’s Binary Encounter Theory, based on Rutherford’s formula $\frac{d\sigma}{d\Omega} = \left(\frac{qe^2}{4E}\right)^2 \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$ where q is the charge state of the impinging ion (Gryzinsky 1965). Experiments involving the production of the BEEs in collisions of 1-2 MeV/u bare C, N, O, and F ions with H_2 and He targets are in excellent agreement with the q^2 scaling law of the Rutherford formula which states that the cross section increases as the charge state q of the ion increases (Lee *et al* 1990).

Another experiment investigating the projectile charge state dependence of BEE production in collisions of 19 and 28.5 MeV $F^{(3-9)+}$ with H_2 and He targets found that BEE production is increasingly enhanced with decreasing projectile charge state q (Richard *et al* 1990) when the projectile is not bare, but brings electrons into the collision. This result is in direct contradiction to the expectations of the q^2 scaling rule (Gryszinsky 1987, Toburen *et al* 1981).

The classical binary encounter approximation for Coulomb interactions (Gryszinsky 1987) was extended to non-Coulomb potentials to reproduce the experimental data for partially stripped ions (Reinhold *et al* 1990). Calculations based on the CTMC model (Olson *et al* 1990) for the BEE production cross section for heavy ion impact on Ar show that the screened projectile potential can significantly enhance the cross section for binary encounter electron ejection in the forward direction.

The energy of the binary encounter peak is expected to be four times that of the cusp peak. This would be the case if a projectile ion collided with a free electron in a binary encounter collision, but the electron is initially bound to a target. Thus, the energy of the binary encounter electron is always less than four times the cusp energy. The energy shift of the BEE peak has been investigated theoretically by a model based on the Bohr-Lindhard (BL) model (Pedersen *et al* 1991, Fainstein *et al* 1992). The main idea behind the BL model is that ionization takes place in the initial channel at some internuclear distance where the attractive force of the incoming heavy ion equals the

binding force of the target on the electron (Fainstein *et al* 1992). Experimental tests of both the Pederson (Pedersen *et al* 1991) and the Fainstein (Fainstein *et al* 1992) models can approximately predict the q dependence of the binary encounter peak energy shift, but the experiments to date have not verified that the shift depends solely on the net projectile charge (Sanders *et al* 1997). Experiments involving the determination of the binary encounter peak energy for 0.6 MeV/u O, F, Si, Ti, Cu, and Br ions, all with $q = 7$, colliding with H_2 targets show that the binary encounter peak energy increases for fixed q (projectile charge state) and increasing Z . This trend is opposite of that observed when Z is fixed and the projectile charge q is varied, and it demonstrates that the binary encounter peak energy depends not only on the net projectile charge but on the projectile core as well (Sanders *et al* 1997).

The focus of this work is the production of target binary encounter electrons (BEE's) near the forward direction, i.e. the production of free electrons in head-on collisions between the projectile nucleus and an outer-shell target electron. We study the production of the BEE and its dependence on the recoil ion charge states and the exit charge states of the projectile ions.

Recently, many experiments have tried to systematically determine the binary encounter electron production cross section as a function of the incident charge state of the projectile (Sanders *et al* 1995), the exit charge state of the projectile ions (Quinteros *et al* 1991), and the charge state of the recoil ions (Segner *et al* 1996).

These experiments usually do not gather all the information that is needed to characterize the collision completely, but concentrate on a particular subset of this information. In many instances, this is due to the limitations of the experimental apparatus. The experiment described here represents an attempt to characterize BEE production for one particular ion-atom collision system. The collision partners are chosen such that all outgoing particles are being detected. These are the projectile ion, the recoil ion, and the binary encounter electron. The collision system is chosen so that no other target or projectile electrons are emitted. Selecting such a simple collision system allows us to compare the experimental results with the theoretical predictions obtained by using the impulse approximation.

CHAPTER 2

THEORY

2.1 IMPULSE APPROXIMATION

In this work, the energy and angular distribution of electrons ejected within 0° to 8° with respect to the beam direction is measured for the 0.5 MeV/u C^{2+} on H_2 collision system. The energies of the measured electrons range from 0 to 1450 eV. The experimental yields are converted into doubly differential cross sections and are compared to theoretical predictions obtained using the Impulse Approximation.

The impulse approximation describes fast ion-atom collisions well when the nuclear charges of the projectile and the target are asymmetric, i.e. either $Z_p \ll Z_t$ or $Z_p \gg Z_t$ where Z_p and Z_t are the projectile and the target nuclear charges, respectively (Jakubassa-Amundsen 1994). The impulse approximation assumes that the only collision partners are the target electron and the screened projectile nucleus (if the projectile carries any electrons into the collision); the target nucleus is considered a spectator whose only purpose is to provide the initial momentum distribution of the target electron. In order to simplify calculations, the impulse approximation calculations are carried out in the center of mass frame; the center of mass frame is equivalent to the projectile frame since $\frac{m_e}{m_p} \ll 1$. The theoretically obtained doubly differential cross sections are then converted into the laboratory frame of reference in

order to compare them with the measured cross sections.

In the projectile frame, the projectile is at rest, and the target electron approaches the projectile with velocity $\mathbf{v} = v\hat{z}$. After a collision, the target electron is scattered through a large angle and exits the collision with velocity $\mathbf{v}_p$. The scattered electron is detected in the laboratory frame within an angular range of 0° to 8° with respect to the beam direction with a velocity $\mathbf{v}_l$ as shown in Figure 2.1.

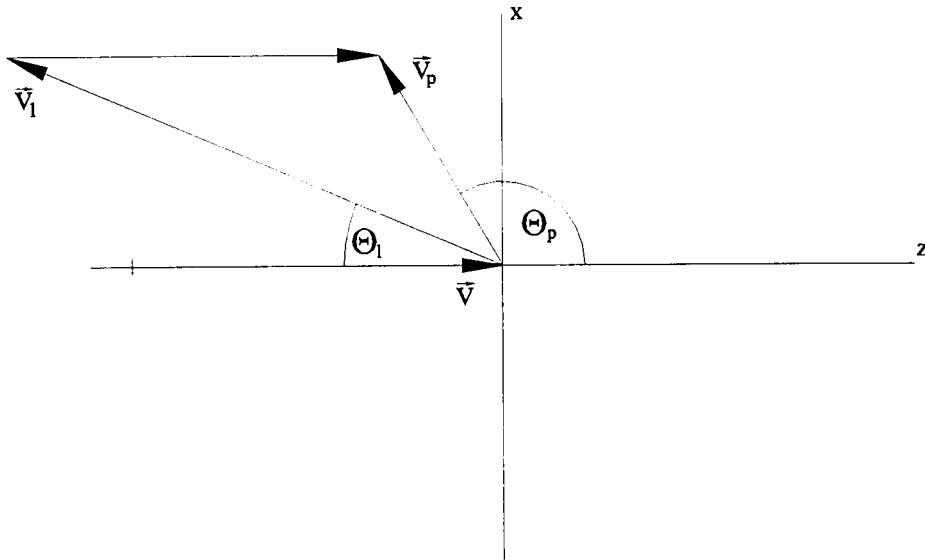


Figure 2.1 Relationship between the scattered electron's velocity $\mathbf{v}_p$ in the projectile frame and its velocity $\mathbf{v}_l$ in the laboratory frame.

The relationship between the laboratory frame velocity $\mathbf{v}_l$ and the projectile frame velocity $\mathbf{v}_p$ is $v + v_p \cos(\pi - \theta_p) = v_l \cos(\theta_l)$, $v_p \sin(\pi - \theta_p) = v_l \sin(\theta_l)$. These

relationships yield the relationship between the laboratory frame scattering angle and the projectile frame scattering angle as

$$\tan(\theta_p) = \frac{\sin(\theta_l)}{\frac{v}{v_l} - \cos(\theta_l)} \quad (2.1)$$

Once θ_p is determined, the velocity in the projectile frame v_p is obtained from

$$v_p = v_l \frac{\sin(\theta_l)}{\sin(\pi - \theta_p)} \quad (2.2)$$

To calculate the doubly differential scattering cross section $\frac{d^2\sigma}{dE d\Omega}$ in the projectile frame we start with the result of formal scattering theory. Let H be the Hamiltonian of the system which can be decomposed into two parts $H_0 + V$; further assume that V is not effective in the remote past and the far future. Therefore, the Hamiltonian $H = H_0 + V$ can be replaced by H_0 in the remote past, $t \rightarrow -\infty$, and in the far future, $t \rightarrow \infty$. Let $\{|\phi_a\rangle\}$ be the eigenstates of H_0 with the eigenvalues E_a , so that $H_0|\phi_a\rangle = E_a|\phi_a\rangle$. The time dependence of $|\phi_a\rangle$ is represented by $|\phi_a(t)\rangle = |\phi_a\rangle e^{-\frac{iE_a t}{\hbar}}$. Assume that the system in the remote past is in the state $|\phi_i(t)\rangle$ and it evolves under the influence of the Hamiltonian H into the state $|\psi_i^+(t)\rangle$. The probability that in the far future the system will be found in a state $|\phi_f(t)\rangle$ is obtained from the square of the transition amplitude S_{if} (Schiff 1968) which is given by

$$S_{if} = \langle \phi_f | S | \phi_i \rangle = \langle \phi_f | \phi_i \rangle - \frac{i}{\hbar} \int dt \langle \phi_f(t) | V | \psi_i^+(t) \rangle \quad (2.3)$$

The quantum mechanical impulse approximation represents an attempt to approximately describe many-body scattering in terms of known two-body scattering

amplitudes (McDowell and Coleman 1970). Consider a simple collision between a proton with velocity v and a hydrogen atom. Let particle 1 be the proton projectile, particle 2 be the hydrogen atom nucleus, and particle 3 be the electron. The Hamiltonian of the system is $H = T + V_{12} + V_{13} + V_{23}$. If protons are regarded as classical particles with infinite mass, their interaction potential may be represented in terms of the velocity v and the impact parameter b .

$$V_{12} = \frac{e^2}{r_{12}} = \frac{e^2}{\sqrt{b^2 + v^2 t^2}} \quad (2.4)$$

Since V_{12} is a known function of time, it can be removed from the Hamiltonian with a canonical transformation. The Schrödinger equation for the system is $H|\psi\rangle = i\hbar \frac{\partial}{\partial t}|\psi\rangle$. Define a new state vector $|\chi\rangle$ so that $|\chi\rangle = e^{-iS(t)}|\psi\rangle$. If $\hbar \frac{dS}{dt} = -V_{12}$, then the state vector $|\chi\rangle$ satisfies the new Schrödinger equation $(T + V_{13} + V_{23})|\chi\rangle = i\hbar \frac{d}{dt}|\chi\rangle$. It is important to note that the state vectors $|\chi\rangle$ and $|\psi\rangle$ only differ by an unobservable phase factor. If protons are regarded as infinitely massive particles, the removal of V_{12} has no physical effect and cannot influence any electronic processes. For a proton of finite mass, neglecting V_{12} corresponds to neglecting terms on the order of $\frac{m_e}{m_p}$. The Hamiltonian of the collision system is now $H = T + V_{23} + V_{13}$; however, the initial and final unperturbed state vectors satisfy the following equations

$$H_0|\phi_i\rangle = E_i|\phi_i\rangle \quad (2.5)$$

$$H_0|\phi_f\rangle = E_f|\phi_f\rangle \quad (2.6)$$

where $H_0 = T + V_{23}$, $|\phi_i\rangle$ is the initial state, and $|\phi_f\rangle$ is the final state of the ejected

electron. The scattering amplitude is given by

$$S_{ifb} = -\frac{i}{\hbar} \int dt \langle \phi_f(t) | V_{13} | \psi_{ib}^+(t) \rangle \quad (2.7)$$

where $|\psi_{ib}^+(t)\rangle$ is the exact state vector that evolves from $|\phi_i(t)\rangle$ in the remote past under the influence of V_{13} and V_{23} if the impact parameter of the collision is b .

One of the assumptions made in the impulse approximation is that V_{23} does not play a major role in the collision dynamics except for providing the bound electron with its initial momentum distribution. Thus, the exact state vector $|\psi_{ib}^+(t)\rangle$ is replaced by the state vector that evolves from $|\phi_i\rangle$ under the influence of only V_{13} . $|\psi_{ib}^+(t)\rangle$ is replaced by $\int d^3q e^{-i(\mathbf{q}-\mathbf{v})\cdot\mathbf{r}} \tilde{\phi}_i(\mathbf{q}-\mathbf{v}) |\psi_q^+\rangle e^{-i(\frac{v^2}{2} + \varepsilon_i)t}$ where $\mathbf{r} = \mathbf{b} + \mathbf{v}t$ and $\tilde{\phi}_i(\mathbf{q}-\mathbf{v})$ is the momentum space wave function of the initial state in the target frame. $|\psi_q^+\rangle$ is the state vector of an electron, with initial momentum $\mathbf{q}$, scattered by the potential V_{13} alone. In order to simplify the notation, atomic units have been used (i.e. $m_e = \hbar = e = 1$). Particle 3 is regarded as a free particle, and its three body scattering amplitude is found by averaging the scattering amplitudes of two free particles over the corresponding momentum distribution. If an electron scatters through a large angle, $\mathbf{k} - \mathbf{v}$ is large, and the final state can be represented by a plane wave.

$$|\phi_f(t)\rangle = e^{-i\mathbf{k}_f\cdot\mathbf{b}} |\mathbf{k}_f\rangle e^{-iE_f t} \quad (2.8)$$

Thus, the expression for scattering amplitude becomes

$$S_{ifb} = -ie^{i\mathbf{k}_f\cdot\mathbf{b}} \iiint d^3q \int_{-\infty}^{+\infty} dt e^{i(E_f + \frac{v^2}{2} - \varepsilon_i - \mathbf{q}\cdot\mathbf{v})t} e^{-i\mathbf{q}\cdot\mathbf{b}} \tilde{\phi}_i(\mathbf{q}-\mathbf{v}) \langle \mathbf{k}_f | V_{13} | \psi_q^+ \rangle \quad (2.9a)$$

$$S_{ifb} = -2\pi i e^{i\mathbf{k}_f\cdot\mathbf{b}} \iiint d^3q \delta\left(\mathbf{q}\cdot\mathbf{v} - E_f - \frac{v^2}{2} - \varepsilon_i\right) e^{-i\mathbf{q}\cdot\mathbf{b}} \tilde{\phi}_i(\mathbf{q}-\mathbf{v}) \langle \mathbf{k}_f | V_{13} | \psi_q^+ \rangle \quad (2.9b)$$

$|S_{ifb}|^2 d^3 k_f$ is the probability of a transition that yields an electron with $\mathbf{k}_f$ in the momentum space volume element $d^3 k_f$. If the square of the transition amplitude is integrated over all impact parameters, the expression for the doubly differential cross section is

$$\frac{d\sigma}{dk_f} \frac{1}{k_f} \frac{d^2\sigma}{dE_f d\Omega} = \iint d^2 b |S_{ifb}|^2 \quad (2.10)$$

$$\begin{aligned} \iint db_x db_y |S_{ifb}|^2 &= \iint db_x db_y 4\pi^2 \iiint d^3 q \iiint d^3 q' f(\mathbf{q}) f^*(\mathbf{q}') e^{-i(\mathbf{q}-\mathbf{q}')_x b_x} e^{-i(\mathbf{q}-\mathbf{q}')_y b_y} \\ &= \frac{16\pi^4}{v^2} \iiint d^3 q' g(\mathbf{q}) g^*(\mathbf{q}') \delta(q_\perp - q'_\perp) \delta(q_\parallel - \frac{E_f}{v} - \frac{v}{2} + \frac{\epsilon_i}{v}) \delta(q'_\parallel - \frac{E_f}{v} - \frac{v}{2} + \frac{\epsilon_i}{v}) \\ &= \frac{16\pi^4}{v} \iiint d^3 q |g(\mathbf{q})|^2 \delta(\mathbf{q} \cdot \mathbf{v} - E_f - \frac{v^2}{2} + \epsilon_i) \end{aligned}$$

where $E_f = \frac{k_f^2}{2}$.

Therefore,

$$\frac{d^2\sigma}{dE_f d\Omega} = \frac{k_f}{v} 16\pi^4 \iiint d^3 q |\phi_i(\mathbf{q} - \mathbf{v}) < \mathbf{k}_f | V_{1,3} | \psi_q^+ >|^2 \delta(\mathbf{q} \cdot \mathbf{v} - (E_f + \frac{v^2}{2} - \epsilon_i)) \quad (2.11)$$

This is the exact result of the impulse approximation with plane-wave final states

(Wang *et al* 1991). It contains the exact off-shell two body T-matrix element

$$T_{fi}(\mathbf{k}_f, \mathbf{q}) = \langle \mathbf{k}_f | V_{1,3} | \psi_q^+ \rangle.$$

Various forms of On Shell Approximations (OSA) can now be invoked. The goal of an on-shell approximation is to first replace the δ - function in Equation 2.11 and to convert the expression for the DDCS into one that contains only the on-shell two-body T-matrix element. The on-shell T-matrix element squared, $|T_{if}|^2$, is proportional to the elastic scattering cross section for free electrons colliding with the projectile ion. The expression for this elastic scattering cross section is $\sigma_{el}(E, \cos(\theta)) = 16\pi^4 |T_{fi}|^2$.

In order to calculate the production cross section for the "high energy" electrons detected in our experiment, an OSA essentially equivalent to the Elastic Scattering Model (ESM) of Bruch, Wieman, and Ingalls (Bruch *et al* 1973) is used. $\tilde{\phi}_i(\mathbf{q} - \mathbf{v})$ in Equation 2.11 is the initial momentum distribution of the target electrons involved in the collision. In the ESM, it is assumed that this electron momentum distribution is sharply peaked around $\mathbf{q} - \mathbf{v} = 0$; therefore, $\mathbf{q} \cong \mathbf{v}$. This leads to

$$(\mathbf{q} - \mathbf{v})^2 = q^2 + v^2 - 2(\mathbf{q} \cdot \mathbf{v}) = 0 \quad (2.12)$$

or

$$\mathbf{q} \cdot \mathbf{v} = \frac{q^2 + v^2}{2} \quad (2.13)$$

The δ -function in Equation 2.11 therefore requires

$$\mathbf{q} \cdot \mathbf{v} = \frac{q^2 + v^2}{2} = \frac{k_f^2 + v^2 - 2\varepsilon_i}{2} \quad (2.14)$$

which is a constraint on the magnitude of q .

$$q^2 = k_f^2 - 2\varepsilon_i \quad (2.15)$$

The expression for DDCS now becomes

$$\frac{d^2\sigma}{dE_f d\Omega} = \frac{32\pi^4 k_f}{v} \iiint d^3q |\tilde{\phi}_i(\mathbf{q} - \mathbf{v}) T_{if}(\mathbf{k}_f, \mathbf{q})|^2 \delta(q^2 - k_f^2 + 2\varepsilon_i) \quad (2.16)$$

and after using the properties of the δ -function, it reduces to

$$\frac{d^2\sigma}{dE_f d\Omega} = \frac{16\pi^4 k_f q_0}{v} \iint |\tilde{\phi}_i(\mathbf{q}_0 - \mathbf{v}) T_{if}(\mathbf{k}_f, \mathbf{q}_0)|^2 d\Omega_{q_0} \quad (2.17)$$

In the elastic scattering model $16\pi^4 \frac{q_0}{v} T_{if}(\mathbf{k}, \mathbf{q}_0)$ is now replaced by $\sigma_{el}(E, \cos(\theta_{eff}))$

where $E = \frac{q_0^2}{2} = \frac{k_f^2}{2} - \varepsilon_i$ and $\cos(\theta_{eff}) = 1 - \frac{|q_0 - k_f|^2}{2q_0^2}$. Figure 2.2 demonstrates how the $\cos(\theta_{eff})$ term conserves the exact momentum transfer during the elastic scattering.

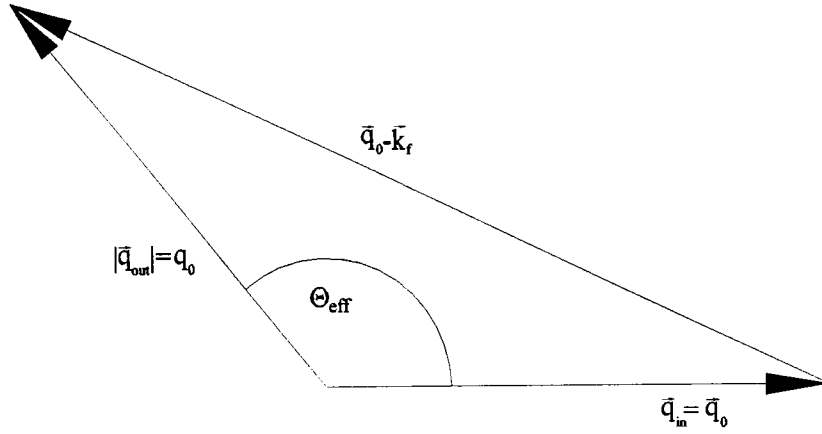


Figure 2.2 $|q_0 - k_f| = q_0^2 + q_0^2 - 2q_0^2 \cos(\theta_{eff})$

The doubly differential cross section for the production for the binary encounter electrons in the projectile frame is then given by

$$\frac{d^2\sigma}{dE_f d\Omega} = k_f \iint \sigma_{el}(\frac{q_0^2}{2}, \cos(\theta_{eff})) |\tilde{\phi}_i(q_0 - v)|^2 d\Omega_{q_0} \quad (2.18)$$

Other forms of on-shell approximations can be used to find the DDCS for the production of binary encounter electrons. One particular form, called OSA 1 (Wang *et al* 1991), was first introduced by Hartley and Walters (Hartley and Walters 1987).

In this OSA, the off-shell T-matrix element $16\pi^4 |T_{fi}(\mathbf{k}_f, \mathbf{q})|^2$ in Equation 2.17 is replaced by the free electrons elastically scattering cross section $\sigma_{el}(E, \cos(\theta_{eff}))$ where $E = \max(\frac{k_f^2}{2}, \frac{q^2}{2})$ and $\cos(\theta_{eff}) = 1 - \frac{|\mathbf{q} - \mathbf{k}_f|^2}{4E}$. The DDCS for the production of the binary encounter electrons ejected with momentum $\mathbf{k}_f$ in the projectile frame is then given by

$$\frac{d^2\sigma}{dE d\Omega} = \frac{k_f}{v} \int dq_{\perp} \sigma_{el}(E, \cos(\theta_{eff})) |\tilde{\phi}_i(\mathbf{q} - \mathbf{v})|^2 \quad (2.19)$$

where the assumptions of OSA 1 are used.

2.2 CALCULATION DETAILS

In this work, doubly differential cross sections $\frac{d^2\sigma}{dE d\Omega}$ for the production of binary encounter electron production in 0.5 MeV/u C^{2+} on H_2 collisions are calculated using the elastic scattering model and OSA 1. The ESM calculations will now be described in detail. Calculations are carried out in the projectile frame of reference, and the results are then converted into the laboratory frame of reference. The projectile frame coordinate system is chosen such that the final momentum $\mathbf{k}_f$ of the ejected electron lies in the x-z plane as shown in Figure 2.3.

Assume that the target electron approaches the projectile with velocity $\mathbf{v} = v\hat{\mathbf{z}}$ in the projectile frame. Then the components of $\mathbf{k}_f$ may be written as

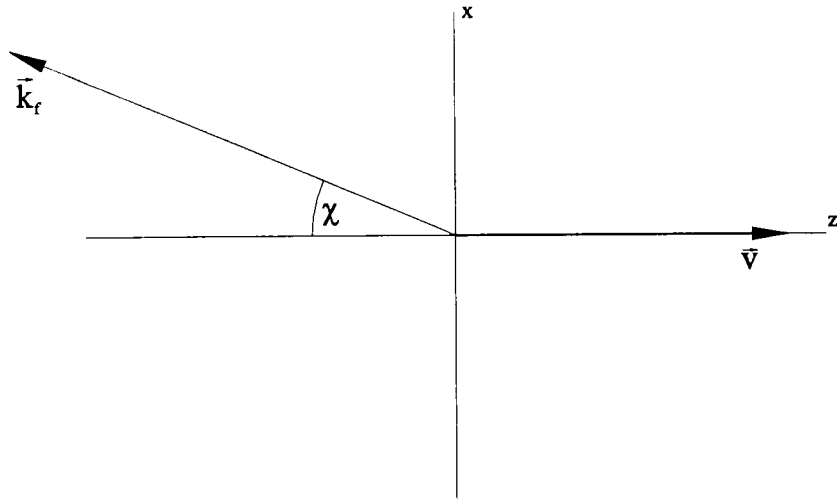


Figure 2.3 Coordinate system chosen for the calculations.

$$\mathbf{k}_f = -k_f \cos(\chi) \hat{\mathbf{z}} + k_f \sin(\chi) \hat{\mathbf{x}} \quad (2.20)$$

$\mathbf{k}_f$ does not have a component in the $\hat{\mathbf{y}}$ direction since it lies strictly in the x-z plane.

The initial momentum $\mathbf{q}_0$ of the electron may be written as

$$\mathbf{q}_0 = q_0 \sin(\theta) \cos(\phi) \hat{\mathbf{x}} + q_0 \sin(\theta) \sin(\phi) \hat{\mathbf{y}} + q_0 \cos(\theta) \hat{\mathbf{z}} \quad (2.21)$$

where θ and ϕ are the usual polar coordinates. In order to evaluate $\phi_i(\mathbf{q}_0 - \mathbf{v})$, the difference between $\mathbf{q}_0$ and $\mathbf{v}$ has to be known. For this, $\mathbf{q}_0$ is broken down into components parallel and perpendicular to the z-axis, $q_{0\parallel} = q_0 \cos(\theta)$, $q_{0\perp} = q_0 \sin(\theta)$.

Therefore,

$$\phi_i(\mathbf{q}_0 - \mathbf{v}) = \phi_i(\sqrt{(q_{0\parallel} - v)^2 + q_{0\perp}^2}) \quad (2.22)$$

To find $\cos(\theta_{eff})$ in Equation 2.18, $|q_0 - k_f|^2$ has to be found first. From Equations 2.20 and 2.21,

$$|q_0 - k_f|^2 = (q_0 \cos(\theta) + k_f \cos(\chi))^2 + (q_0 \sin(\theta) \cos(\phi) - k_f \sin(\chi))^2 + (q_0 \sin(\theta) \sin(\phi))^2 \quad (2.23)$$

Therefore, Equation 2.18 becomes

$$\frac{d^2\sigma}{dE_f d\Omega} = k_f \iint d\theta d\phi \sin(\theta) \sigma_{el}(\theta, \phi) |\phi_i(\theta)|^2 \quad (2.24)$$

For a given k_f , $\sigma_{el}(\theta, \phi)$ and $\phi_i(\theta)$ can be evaluated for all values of the integration variables θ and ϕ .

To evaluate this expression, one needs to determine $\sigma_{el}(k, \theta, \phi)$, the elastic scattering cross section for free electrons scattering off the projectile ion as a function of electron energy and scattering angle, and the initial momentum space wave function of the scattered electrons $\phi_i(q_0 - v)$. Since the scattered electrons are initially not free but bound, the binding energy ε_i also has to be known.

To calculate the cross section for the elastic scattering of an electron by the spherically symmetric potential of a projectile ion, we start with the time-independent Schrödinger equation for the problem.

$$\left[-\frac{\hbar^2}{m} \nabla^2 + V(r) \right] \psi(r) = E \psi(r) \quad (2.24)$$

Let $k = \sqrt{\frac{2mE}{\hbar^2}}$. The asymptotic form of $\psi(\mathbf{r})$ is $\psi(\mathbf{r}) = e^{ikz} + f(\theta)\frac{e^{ikr}}{r}$. The

differential scattering cross section is given by $\frac{d\sigma}{d\Omega} = |f(\theta)|^2$. We need to find $f(\theta)$.

Assume $V(r) = Cr^{-1}$. There is an analytic solution of the time-independent Schrödinger equation which is regular at the origin and fulfills asymptotic boundary conditions appropriate to the scattering problem (Friedrich 1991).

$$\psi(\mathbf{r}) = Ne^{-\frac{\pi\eta}{2}} \Gamma(1+i\eta) e^{ikz} F(-i\eta, 1; ik(r-z)) ; \quad \eta = \frac{Cm}{\hbar^2 k} \quad (2.25)$$

The asymptotic form through terms of the order of $\frac{1}{r}$ is

$$\psi(\mathbf{r}) = N \left\{ e^{i(kz - \eta \ln k(r-z))} \left[1 + \frac{\eta^2}{ik(r-z)} \right] + \frac{1}{r} f_c(\theta) e^{i(kr - \eta \ln 2kr)} \right\} \quad (2.26)$$

$$f_c(\theta) = \frac{-\eta}{k \sin^2 \frac{\theta}{2}} e^{2i\eta_0 - 2i\eta \ln \sin \frac{\theta}{2}} ; \quad \eta_0 = \arg \Gamma(1+i\eta) \quad (2.27)$$

If $\psi(\mathbf{r})$ is expanded in terms of spherical partial waves, $\psi(\mathbf{r}) = \sum_{l=0}^{\infty} R_l(r) P_l(\cos \theta)$, the

asymptotic form of $R_l(r)$ becomes (Schiff 1968)

$$R_l(r) \xrightarrow{r \rightarrow \infty} N \frac{\sin\left(kr - \frac{1}{2}l\pi - \eta \ln 2kr + \eta_l\right)}{kr} \quad (2.28)$$

where $\eta_l = \arg \Gamma(l+1+i\eta)$. Now assume the modified Coulomb potential

$V(r) = Cr^{-1} + V_{sc}(r)$, $\lim_{r \rightarrow \infty} r^2 V_{sc} = 0$. Expanding $\psi(\mathbf{r}) = \sum_{l=0}^{\infty} R_l(r) P_l(\cos \theta)$, the

asymptotic form of $R_l(r)$ becomes

$$R_l(r) \xrightarrow{r \rightarrow \infty} N \frac{\sin\left(kr - \frac{1}{2}l\pi - \eta \ln 2kr + \eta_l + \delta_l\right)}{kr} \quad (2.29)$$

and

$$f(\theta) = f_c(\theta) + \sum_{l=0}^{\infty} \frac{1}{k} (2l+1) e^{i(2\eta_l + \delta_l)} \sin \delta_l P_l(\cos \theta) \quad (2.30)$$

For a C^{2+} in the ground state, $V(r)$ is given by

$$V(r) = \frac{e^2}{r} [4(1 - \{1.15287(e^{4.9017r} - 1) + 1\}^{-1}) - 6] \quad (2.31)$$

where the distances are measured in angstroms and energies are in eV (Garvey *et al*

1975). To find $\frac{d\sigma}{d\Omega} = |f(\theta)|^2$, δ_l must be calculated. For $V(r) = Cr^{-1}$ and

$V(r) = Cr^{-1} + V_{sc}(r)$, the radial equation is solved numerically and $u_l(r)$ is found.

$$\frac{d^2}{dr^2} u_l(r) + k_l^2 u_l(r) = 0; \quad k_l^2 = \frac{2m}{\hbar^2} \left[E - \frac{l(l+1)\hbar}{2mr^2} - V(r) \right] \quad (2.32)$$

The Numerov algorithm yields

$$\left[1 + \frac{dr}{12} k_l^2(r_{k+1}) \right] u_l(r_{k+1}) - 2 \left(1 - \frac{5dr^2}{12} k_l^2(r_k) \right) u_l(r_k) + \left(1 + \frac{dr^2}{12} k_l^2(r_{k-1}) \right) u_l(r_{k-1}) = 0 \quad (2.33)$$

$$u_l(r_{k+1}) = \frac{\left[2 - \frac{10dr^2}{12} k_l^2(r_k) \right] u_l(r_k) - \left[1 + \frac{dr^2}{12} k_l^2(r_{k-1}) \right] u_l(r_{k-1})}{1 + \frac{dr^2}{12} k_l^2(r_{k+1})} \quad (2.34)$$

For $V(r) = Cr^{-1}$,

$$u_l(r) \xrightarrow{r \rightarrow \infty} A \sin \left(kr - \frac{1}{2} l\pi - \eta \ln 2kr + \eta_l \right) \quad (2.35)$$

For $V(r) = Cr^{-1} + V_{sc}(r)$,

$$u_l^+(r) \xrightarrow{r \rightarrow \infty} B \sin \left(kr - \frac{1}{2} l\pi - \eta \ln 2kr + \eta_l + \delta_l \right). \quad (2.36)$$

Let us pick two values, r_1 and $r_2 = r_1 + \Delta r$. Then

$$u_l(r_1) = A \sin x_1 \quad (2.37)$$

$$u_l(r_2) = A \sin(x_1 + \Delta x) = u_l(r_1) \cos \Delta x + A \cos x_1 \sin \Delta x \quad (2.38)$$

$$\Delta x = k(r_2 - r_1) - \eta(\ln 2kr_2 - \ln 2r_1) \quad (2.39)$$

The following two equations have to be solved for x_1

$$\frac{u_l(r_2) - u_l(r_1) \cos \Delta x}{\sin \Delta x} = A \cos x_1 \quad (2.40)$$

$$\frac{u_l(r_1) \sin \Delta x}{u_l(r_2) - u_l(r_1) \cos \Delta x} = \tan x_1 \quad (2.41)$$

Two equations are needed to identify the correct quadrant. Once x_1 is known, δ_l can be found.

$$\frac{u_l^+(r_1) \sin \Delta x}{u_l^+(r_2) - u_l^+(r_1) \cos \Delta x} = \tan(x_1 + \delta_l) . \quad (2.42)$$

The phase shifts are calculated using a computer program, DELTA.BAS (Appendix A). It generates an output file containing the phase shifts, PHASE.LOG, which is used as an input file by the program CROSS.BAS (Appendix B) to find the elastic scattering cross section σ_{el} .

Finally, the Compton profile for the H_2 molecule yields the initial momentum space wave function of the scattered electron

$$\phi_i(\mathbf{q}_0 - \mathbf{v}) = \frac{a}{(1 + \beta|\mathbf{q}_0 - \mathbf{v}|^2)^4} + \frac{\gamma}{(1 + \zeta|\mathbf{q}_0 - \mathbf{v}|^2)^5} \quad (2.43)$$

where

$$|\mathbf{q}_0 - \mathbf{v}|^2 = (q_{0\parallel} - v)^2 + q_{0\perp}^2 \quad (2.44)$$

All the information is now available to compute the BEE production cross section

from Equation 2.18. This task is accomplished by a computer program, OSAH2ANG.BAS (Appendix C). This program creates an output file that contains the cross section for binary encounter electron production by 0.5 MeV/u C^{2+} on H_2 as a function of energy and angle. Figure 2.4 illustrates how the three calculation programs are connected.

Figure 2.5 shows the BEE production cross section within 0° and 50° of the forward direction for the 0.5 MeV/u C^{2+} on H_2 collision system calculated in the ESM. The details of the calculations using OSA 1 are similar in nature to the details of the calculations using ESM. The results of the OSA 1 calculations for 0° are compared with the results of the ESM calculations in Figure 2.6. The BEE peak calculated using OSA 1 is shifted toward higher energy by approximately 10 eV compared to the ESM peak. The cross section at the peak is slightly smaller for OSA 1 as compared to that of the ESM.

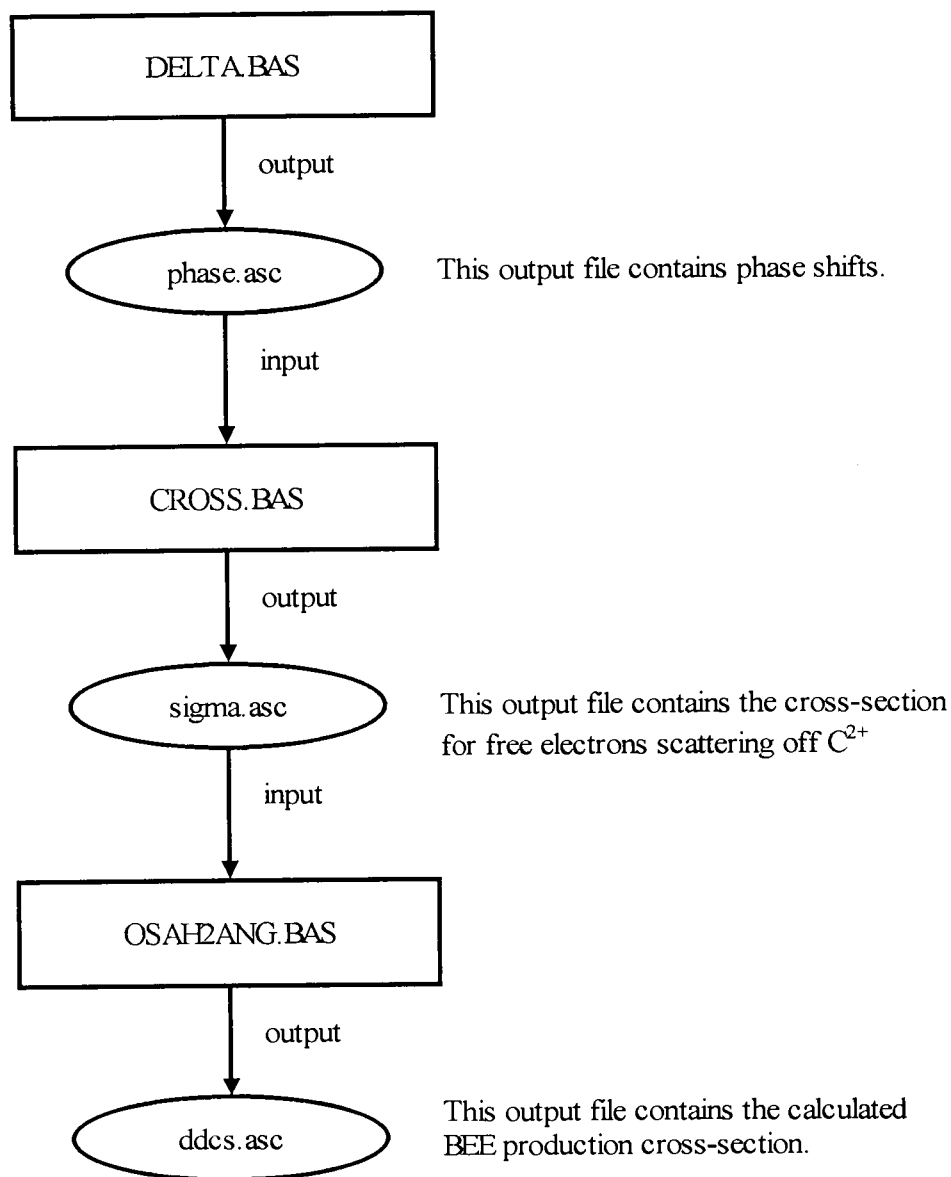


Figure 2.4 Flowchart for the computer programs used to calculate the BEE production cross section for 0.5 MeV/u C^{2+} on H_2 .

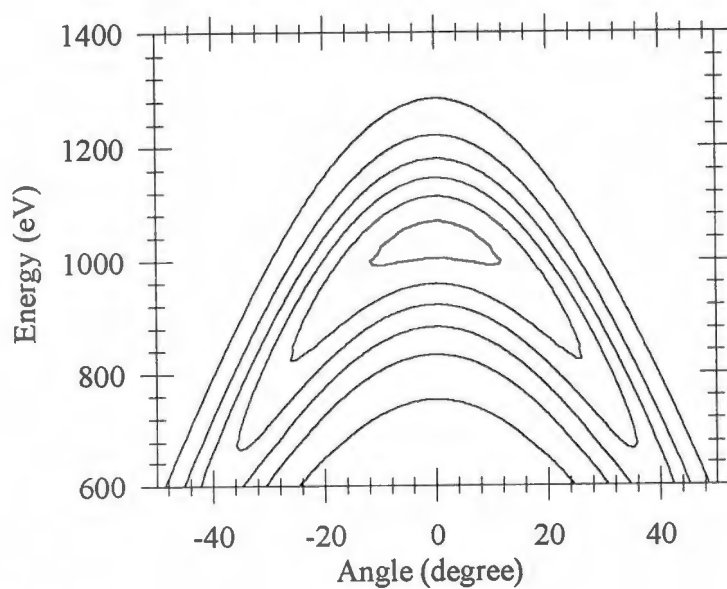
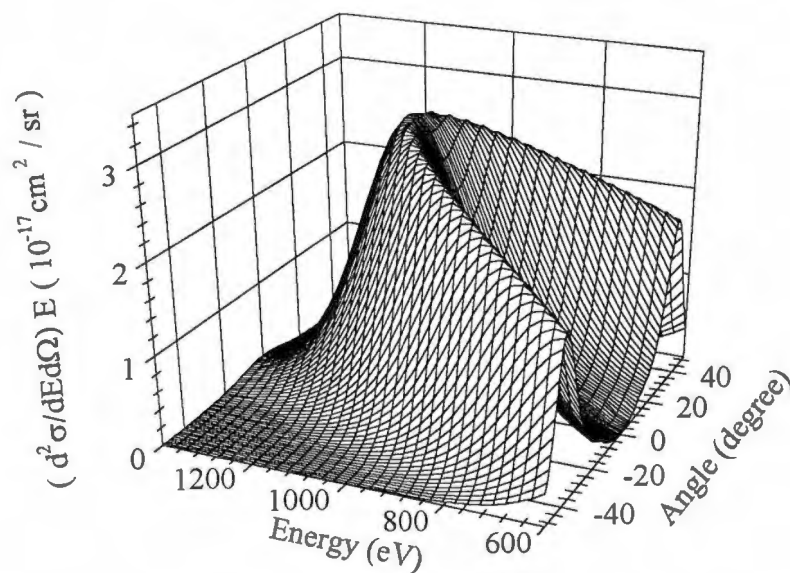


Figure 2.5 BEE production cross section for 0.5 MeV/u C^{2+} on H_2 calculated in the ESM. The contour lines within the bottom figure are placed at intervals of $5 \times 10^{-18} \text{ cm}^2/\text{sr}$.

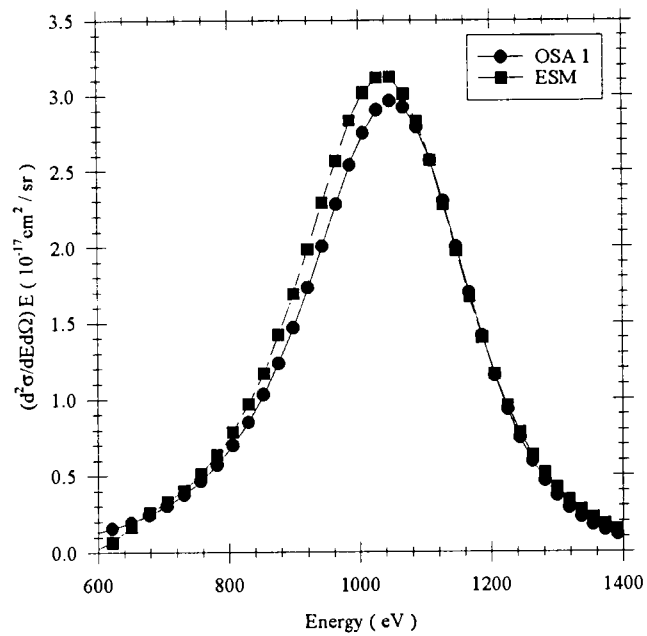


Figure 2.6 Comparison of the DDCS at 0° calculated using OSA 1 and the ESM.

CHAPTER 3

EXPERIMENTAL APPARATUS

3.1 INTRODUCTION

In this experiment, the production cross section for electrons ejected within 8° of the forward direction is measured as a function of energy and angle for the collision system of $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 . These measurements are made in coincidence with selected exit charge states of the projectile ions and a particular charge state of the target recoil ions.

A $0.5 \text{ MeV/u } \text{C}^{2+}$ beam is extracted from the EN-12 Tandem Van de Graff accelerator located at the Oak Ridge National Laboratory. The C^{2+} beam interacts with the H_2 target in the gas cell of a multispectrometer apparatus. Electrons ejected into the forward direction are energy and angle analyzed by a 30° parallel plate electrostatic analyzer. Recoil ions born in the collision are extracted from the gas cell into a Recoil Ion Time of Flight spectrometer (RITOF) and are detected using a channel plate detector. A projectile-ion charge-state analyzer is also part of the experimental setup. It can be used to separate the projectile ions in the beam according to their exit charge state. Ions of a selected charge state are then detected with a single ion detector. When it is not important to determine the exit charge state of the projectile ion, the total beam current is collected in a Faraday cup.

3.2 TANDEM VAN DE GRAFF ACCELERATOR AND BEAM LINE

The measurements are made at the EN-12 Tandem Van de Graff Accelerator facility located at the Oak Ridge National Laboratory. The general layout of the accelerator and beam line is shown in Figure 3.1 .

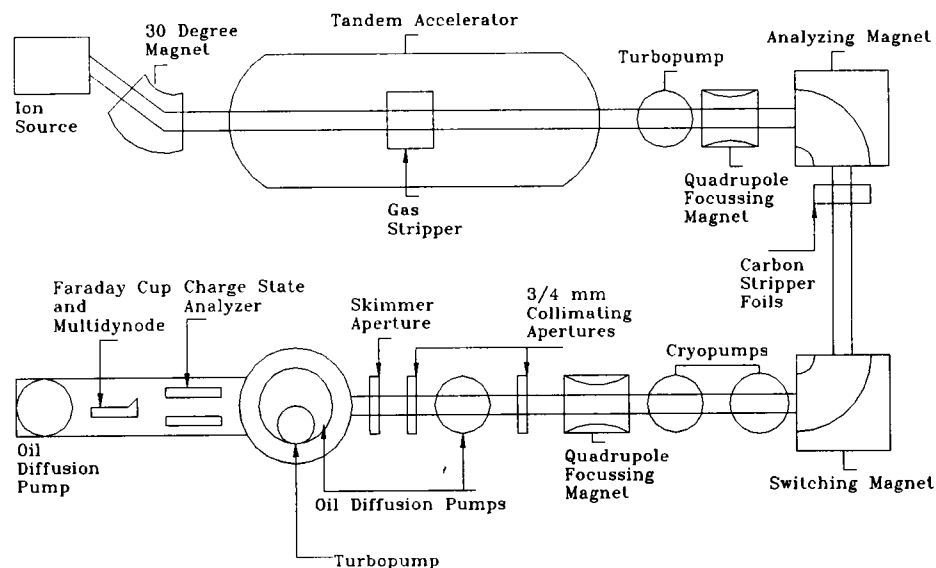


Figure 3.1 A schematic diagram of the EN Tandem Van de Graff Accelerator and beam line.

C⁻ ions are produced in the ion-source by accelerating Cs⁺ ions into a C pellet. These C⁻ ions are electrostatically accelerated through a potential difference of approximately 100 kV. They are then bent by a 30° analyzing magnet and directed into the EN Tandem Van de Graff accelerator. They are attracted toward the positive terminal

which is held at a voltage of 1.192 MV. Argon is used as a stripper gas within the terminal to strip the C^- beam into a C^{q+} beam. The positive ions are then accelerated toward the exit of the accelerator which is held at ground potential. After exiting the accelerator, the ions pass various steering elements and an analyzing magnet. The magnetic field strength here is such that only the projectile ions with the momentum to charge ratio of 0.5 MeV/u C^{2+} ions are transmitted. Carbon ions with other charge states are lost in collisions with the walls of the magnet chamber and the beam line. After the analyzing magnet, the ion beam passes between a pair of slits that define its size. A second 90° "switching magnet" directs the 0.5 MeV/u C^{2+} beam toward our experimental chamber.

Before entering the experimental chamber, the ion beam passes through two apertures approximately 2 m and 0.65 m in front of the target gas-cell. The apertures are 0.5 mm in diameter, and they further collimate the ion beam. A skimmer aperture 1 mm in diameter is located 0.15 m down stream of the second aperture. It does not intercept the collimated beam but "skims off" the ions that are scattered off the second aperture. This skimmer aperture significantly reduces the background in the experimental spectra created by stray ions scattered at large angles from the second aperture. All three apertures are aligned visually before the start of an experiment with the entrance and exit apertures of our multispectrometer apparatus in the experimental chamber. Current on the skimmer aperture is monitored and minimized during an experiment in order to reduce background counts due to misalignment, bad focusing, or improper

steering of the beam. This is accomplished by moving the skimmer aperture in a plane perpendicular to the beam axis.

After passing through the skimmer aperture, a well collimated beam of projectile ions enters the experimental chamber. There it interacts with the H_2 target in the gas-cell region of the spectrometer. It leaves the spectrometer region through a hole in the back of the spectrometer and exits the experimental chamber virtually undeflected.

The ion beam then passes between the parallel plates of a charge state analyzer where the projectile ions can be separated according to their various exit charge states. Ions of a selected exit charge state can then be detected with a single ion detector; when it is not important to identify the exit charge state of the projectile ion, the entire beam is collected in a Faraday cup located at the end of the beam line.

The apertures in the beam line are initially aligned with the apertures in the multispectrometer using a telescope under atmospheric pressure. When the experimental chamber is evacuated, the base of the chamber is observed to flex upward due to the pressure difference inside and outside the chamber. This leaves the multispectrometer apparatus misaligned. In order to remedy this situation, the aligning telescope is intentionally misaligned (at atmospheric pressure) a preset amount with respect to the apertures of the multispectrometer so that, when the experimental chamber is evacuated, the multispectrometer apparatus is left aligned.

The beam line apertures can also be fine adjusted under vacuum.

The base pressure in the experimental chamber is kept below 1×10^{-8} Torr with the help of a diffusion pump directly below and a turbo molecular pump directly above the experimental chamber, along with several diffusion pumps and a cryo pump along the beam line. The pressure in the chamber stays below 1×10^{-6} Torr even after the introduction of the target gas.

3.3 GAS-CELL

The gas-cell is mounted at the entrance of a 30° parallel plate spectrometer. It has a length of 10 mm with a round entrance aperture of 2 mm diameter and a rectangular exit aperture of 2 mm by 3 mm. An aluminum plate covers the top of the gas-cell. This plate has an aperture of 2 mm in diameter which is the gateway for the recoiling target ions to enter the recoil ion time of flight spectrometer. A small rectangular chamber is attached to the bottom of the gas-cell. Gas can flow through the attached gas lines into this chamber. The gas then flows from this chamber into the gas-cell through an opening covered with an 88% transmission grid on the top of the chamber. This grid forms the bottom of the gas-cell and is electrically isolated from the top of the gas-cell. This way a small voltage can be placed across the gas-cell and the recoil ions can be extracted into the RITOF (Figure 3.2).

The pressure in the gas cell and the gas feed lines is measured with two capacitive manometers (MKS Baratron type 270A). In order to maintain a constant pressure in the gas cell, the output of one of the manometers is fed back to a Granville-Phillips

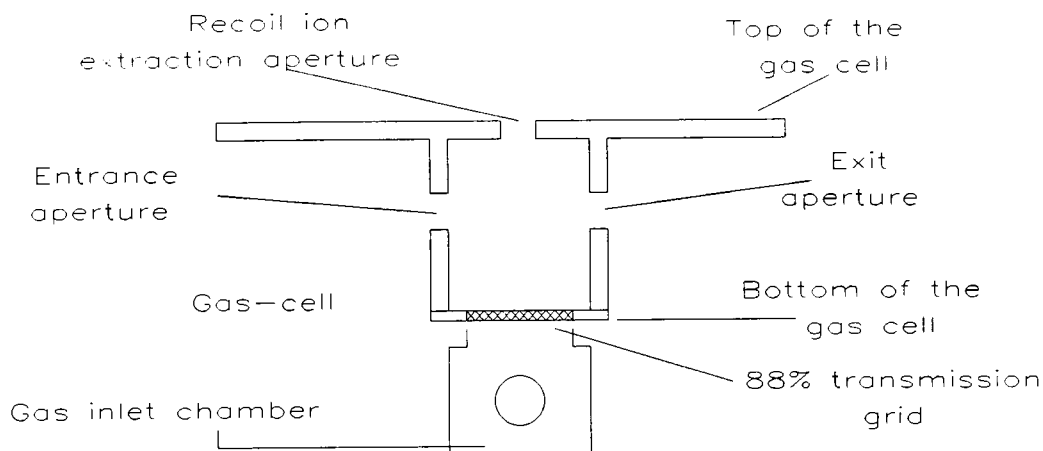


Figure 3.2 A schematic diagram of the gas-cell.

pressure/flow controller (Type 216) which controls a servo driven valve assembly.

This valve controls the gas flow from the gas bottle. Gas-cell pressure fluctuates on the order of 10%, but due to our long data acquisition times, it averages out.

3.4 RECOIL ION TIME OF FLIGHT SPECTROMETER

The purpose of the RITOF is to determine the charge state of the target recoil ions produced in a collision. After extracting the recoil ions from the gas-cell, it measures their flight time to a detector. This flight time depends on the charge state of the recoiling ion.

The RITOF consists of three distinct regions: an extraction region, an acceleration region and a drift region. These three regions are shown in Figure 3.3. The extraction region is the gas-cell. Ions are extracted from the gas cell by a small electric field in the gas-cell. They are then directed into the acceleration region by a stronger electric field. The field free drift region is where the recoil ions spend most of their time before being detected.

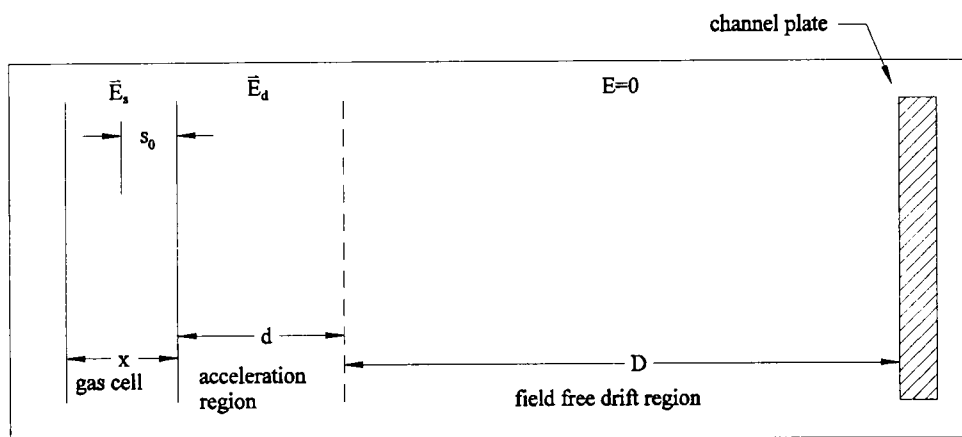


Figure 3.3 Schematic diagram of the Recoil Ion Time Of Flight spectrometer.

The energy of an ion that reaches the detector at the end of the drift region is given by

$$U = U_0 + qsE_s + qdE_d \quad (3.1)$$

where U_0 is the initial kinetic energy of the ion, q is its charge, s is the perpendicular distance from the place where the ion is born to the entrance of the acceleration

region, d is the length of the acceleration region, and E_s and E_d are the electric fields applied in the extraction and acceleration regions, respectively.

The flight time of an ion born with $U'_0 = \frac{1}{2}mv_\perp^2$ to the detector is

$$T(U'_0, s) = T_s + T_d + T_D \quad (3.2)$$

Here

$$T_s = \frac{\sqrt{2m}}{qE_s} \left[\sqrt{U'_0 + qsE_s} \pm \sqrt{U'_0} \right] \quad (3.3)$$

where the $\pm$ signs in the above equation refer to an initial velocity component of the ion toward or away from the detector, respectively. $v_\perp$ is the velocity of the ion perpendicular to the beam direction.

$$T_d = \frac{\sqrt{2m}}{qE_d} \left[\sqrt{U'} - \sqrt{U'_0 + qsE_s} \right] \quad (3.4)$$

$$T_D = \frac{\sqrt{2m} D}{2\sqrt{U'}} \quad (3.5)$$

Every ion is not born the same distance s away from the exit of the extraction region in the gas cell. The beam has a diameter of approximately 1 mm, and the target gas is evenly distributed in the volume of approximately 1 cm³. Therefore, some of the ions are born closer to the detector, $s = s_0 - \Delta s$, and others are born farther away from the detector, $s = s_0 + \Delta s$, where s_0 is the distance from the center of the beam to the end of the extraction region. In order for the same charge state ions born at different places along the cylinder axis to have the same flight time, the RITOF should have good spatial resolution. Spatial resolution is the property of the spectrometer to

resolve different charge to mass ratios of the ions despite their initial space distribution (Wiley and McLaren 1955). In general, this can be accomplished in two different ways; one is to reduce Δs . The second way depends on the fact that ions born further away from the exit of the gas cell will gain more energy in the gas cell and eventually overtake ions born closer to the exit aperture. By adjusting the velocities gained by ions in the extraction and the acceleration regions, their trajectories can be made to intersect at the channel plate. This can be done by adjusting the extraction and acceleration fields and has been done in this work.

The condition for space focusing is achieved in the following manner. If $\frac{dT}{ds}|_{s=s_0} = 0$, the flight time of the ions of charge q to the detector is independent of the path length s in the gas-cell to first order. If $U'_0 = 0$, then $\frac{dT}{ds}|_{s=s_0} = 0$ yields the following relationship between the spectrometer dimensions and the applied electric fields:

$$D = 2s_0 k_0^{\frac{3}{2}} \left(1 - \frac{1}{k_0 + k_0^{\frac{1}{2}}} \frac{d}{s_0} \right) \quad (3.6)$$

where

$$k_0 = 1 + \frac{E_d d}{E_s s_0} \quad (3.7)$$

The values of s_0 , d , and D are fixed from the dimensions of the RITOF. A numerical solution is found for the value of k_0 from which the ratio of E_s/E_d is easily found.

In order to achieve space focusing, it is clear that the values of E_s and E_d cannot be

chosen arbitrarily. The selection of one depends on the other. Choosing a high value of E_s will result in a high count rate for recoil ions, but it will disturb the trajectory of the electron born in the collision in which a recoil ion is produced. The ejected electron, which will be analyzed by another spectrometer, will therefore not retain the correct energy and angular information. Thus, it is important to choose a small value for the extraction field even though it results in a low recoil ion count rate and thus, a low efficiency of the RITOF. The selected value of E_s for this analyzer is 5 V/cm.

3.5 PARALLEL PLATE ANALYZER

The electron analyzer used in this experiment is a single pass 30° parallel plate electrostatic energy analyzer. Such an analyzer is described in detail by T. S. Green and G. A. Proca in a 1970 publication (Green and Proca 1970).

This spectrometer deflects an electron ejected in the gas-cell with energy and emission angle in select ranges towards a position sensitive detector located in the focal plane of the spectrometer. The spectrometer may be divided into three regions as shown in Figure 3.4. Region I includes the gas-cell and the flight path to Region II which is the field region between the two parallel plates. Fringe plates are equally spaced between the two parallel plates and connected via a resistor chain to keep the electric field between the plates as uniform as possible. Neglecting "edge effects," the electric field in Region II is uniform. Region III contains a field free region between the earth plate of the spectrometer and the focal plane. The electrons are brought to a second order

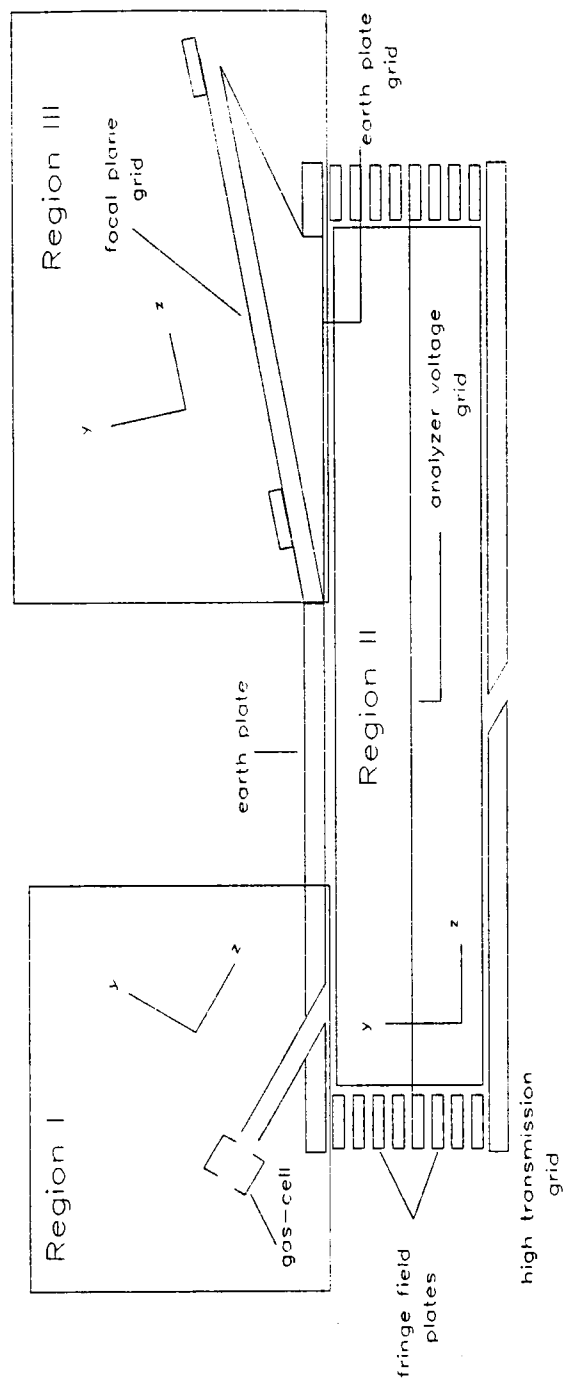


Figure 3.4 Schematic diagram of a 30° parallel plate analyzer.

focus on the focal plane.

If we choose our coordinate system as shown in Region II of Figure 3.4, the trajectory in Region III of an electron ejected in the gas cell is given by the equation

$$Z = h \cot(\theta) + \frac{2T}{F} \sin(2\theta) + Y \cot(\theta) \quad (3.8)$$

where T is the kinetic energy of the electron if emitted with $v_x = 0$ and F is the electric field which is proportional to the analyzer voltage. Electrons which are born with emission angles in the range between θ and $\theta \pm \Delta\theta$ are brought to a first order focus at the location of the detector if $\frac{dZ}{d\theta}$ is zero for a constant value of Y on the focal plane.

$$\frac{dZ}{d\theta} = \frac{4T}{F} \cos(2\theta) - (h + Y) \csc^2(\theta) = 0 \quad (3.9)$$

$$\therefore (h + Y) = \frac{4T}{F} \cos(2\theta) \sin^2(\theta) \quad (3.10)$$

Solving Equation 3.10 for $\frac{T}{F}$ and substituting it into Equation 3.8 shows that the focal positions for various initial energies T lie on a straight line given by the equation

$$Z = (h + Y) \cot(\theta) \left(1 + \frac{1}{\cos(2\theta)}\right) \quad (3.11)$$

or

$$Y = \frac{\tan(\theta) \cos(2\theta)}{(1 + \cos(2\theta))} Z - h \quad (3.12)$$

The slope of this line is $\frac{\tan(\theta) \cos(2\theta)}{(1 + \cos(2\theta))}$, and the Z - intercept is $-h$. Thus, the angle α that the focal line makes with the ground plate of the analyzer is fixed and is solely dependent on the choice of θ .

$$\alpha = \arctan\left(\frac{\cos(2\theta)\tan(\theta)}{1+\cos(2\theta)}\right) \quad (3.13)$$

If the spectrometer is designed for electrons to enter the spectrometer with $\theta = 45^\circ \pm \Delta\theta$, the value of $\alpha = 0^\circ$, and the focal plane coincides with the earth plate. Our spectrometer is designed for electrons to enter the spectrometer at $30^\circ \pm \Delta\theta$, where $\Delta\theta$ is equal to 1.5° , and the value of α is 10.9° . For an entrance angle of 30° , the electrons are brought to a second order focus in the focal plane, and angular aberration is minimized.

Angular aberration is a measure of the difference in the final positions of two electrons born at the same initial position and with the same energy in the source region but with slightly different entrance angles. For example, the final positions Z_1 and Z_2 on the focal plane of electrons that enter the earth plate with angles θ and $\theta + \Delta\theta$ are given by

$$Z_1 = \frac{2T}{F} \sin(2\theta)(1 + \cos(2\theta)) \quad (3.14)$$

and

$$Z_2 = \frac{2T}{F} \sin 2(\theta + \Delta\theta)(1 + \cos 2(\theta + \Delta\theta)) \quad (3.15)$$

respectively. $\frac{\Delta Z}{Z_1} = \frac{Z_2 - Z_1}{Z_1}$ is found, and $\frac{\Delta Z}{Z_1}$ vs $\Delta\theta$ is plotted for two different values of θ , $\theta = 30^\circ$ and $\theta = 45^\circ$ in Figure 3.5. The figure clearly shows that for the entrance angle of 30° the angular aberration remains significantly smaller for larger $\Delta\theta$'s compared to the entrance angle of 45° . Choosing the entrance angle of 30° minimizes the aberration.

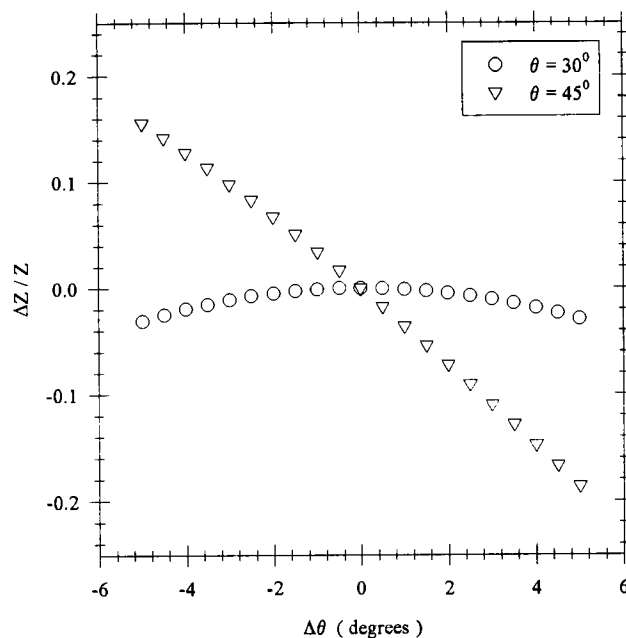


Figure 3.5 Angular aberration as a function of $\Delta\theta$ for two different entrance angles.

Our spectrometer has a large acceptance angle in the x-z plane. Electrons with emission angles between 0° and 8° are accepted. The electric field does not affect the motion of particles in the spectrometer's x-z plane. A particle emitted from the source with its velocity vector v_0 making an angle γ with the Oyz plane will have a velocity $v_0 \cos(\gamma)$ in that plane and a component $v_0 \sin(\gamma)$ perpendicular to that plane. As γ increases, the particle will therefore intercept the focal plane at smaller values of z; one obtains a curved image (Green and Proca 1970).

The 30° parallel plate spectrometer used in this work has been used in two previous

experiments (Freyou 1988, Richards 1992). However, during the course of this research, several modifications were made. The goal of these modifications is to reduce the number of background electrons reaching the detector and to correct distortions of the image at the edges of the detectors. In a generic 30° analyzer, a solid metal plate with an exit hole for the beam is used as the high voltage plate. A slit is cut into the earth plate as an exit aperture for the electrons to reach the detector. In our analyzer, a high transmission grid replaces the solid metal high voltage plate. The grid is held at a negative potential. The top and bottom plates of the analyzer are grounded. A large 11.8 cm by 7.6 cm rectangular hole is cut into the earth plate which serves as an exit aperture for the electrons exiting the parallel plate region. The large acceptance angle of 0° to 8° requires this large opening in the earth plate. This rectangular opening is covered by a high transmission grid. Another high transmission grid is also located at the focal plane. These high transmission grids maximize electron transmission while still preserving a uniform electric field.

The grids used for the analyzer voltage plate, earth plate, and the focal plane are hand made from a thin steel wire with a diameter of 1/1000 inch as shown in Figure 3.6. Fine slits are cut into the aluminum frame 1.5 mm apart with an Exacto knife. A steel wire is then placed into the slit, and the sides of the slit are mashed down causing the wire to hold into place. The wire is pulled to the opposite side of the frame, and the procedure is repeated. These are one dimensional grids which have the transmission efficiency of 99%. The grids made this way increase transmission and nearly eliminate

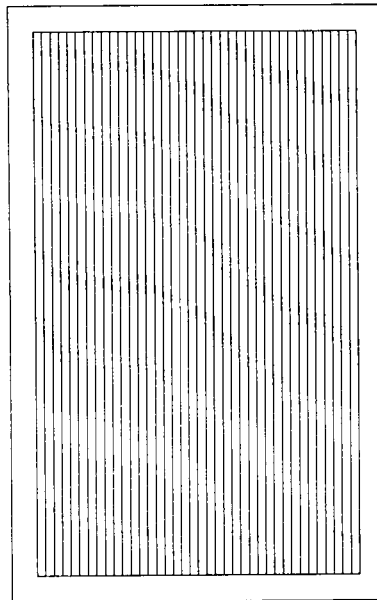


Figure 3.6 Diagram of the handmade grids.

background generated by electrons hitting the grids and producing secondaries, which are then accelerated into the detector. Commercially available woven grids were previously used in this analyzer which reduced detection efficiency and created high background rates. The analyzer's high voltage grid was hardest to make. The schematic diagram of this grid is shown in Figure 3.7.

It was necessary to create an opening in this grid in order for the projectile beam to pass through without any of the projectile ions striking the grids. A great deal of care was taken in determining the optimal size of the opening. If the opening is too large, the electric field distorts resulting in a distorted image on the detector.

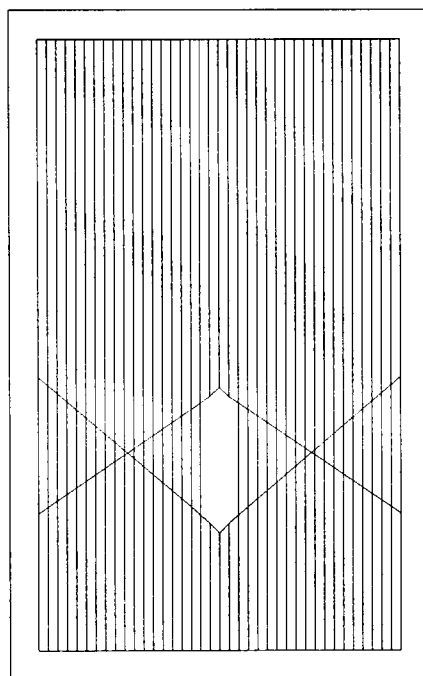


Figure 3.7 Diagram of the handmade analyzer plate grid.

A mount for the position sensitive detector was made, and its position along the focal plane was carefully chosen. As can be seen in Figure 3.4, a large portion of the focal plane “faces” directly into the analyzer. When high energy electrons strike the high voltage grid, they knock out secondaries which will be accelerated by the electric field between the plates directly into the portion of the detector facing into the analyzer. Using the output of a simulation program, the position of the high voltage grid was chosen in such a way that electrons not being bent into the detector will strike opposite the solid part of the ground plate and not opposite the exit hole leading to the detector. In addition, the position sensitive detector was moved along the focal

plane so that smaller portion of the detector “faces” inside the analyzer. These modifications significantly reduce the background but do not completely eliminate it. However, the remaining background is essentially eliminated in our experiments when the electrons are detected with coincidence requirements.

The commercially available micro channel plate assembly was modified in order to rid the image of distortions. A commercially available channel plate assembly consists of the channel plate material sandwiched between two metal frames. These two metal frames are held together by metal screws that are electrically isolated from the frame and the microchannel plate. When electrons strike the screws and insulators during the course of data acquisition, it is difficult to remove the accumulated charge since they are electrically isolated. This results in a high electric field in the vicinity of the screws. This electric field distorts the trajectories of the electrons that strike up to 2 cm from the edges of the channel plate which results in a distorted image on the position sensitive detector. Thus, it was necessary to shave the screws and insulators so they were nearly flush with one of the metal plates and electrically connect the screws to the grounded metal plate as shown in Figure 3.8. This eliminates the image distortions on the position sensitive detector. For this experiment the position sensitive detector was for the first time equipped with a resistive anode position decoder. The anode is commercially available but the necessary electronics to decouple the signals from the high voltage at the four corners was built in house.

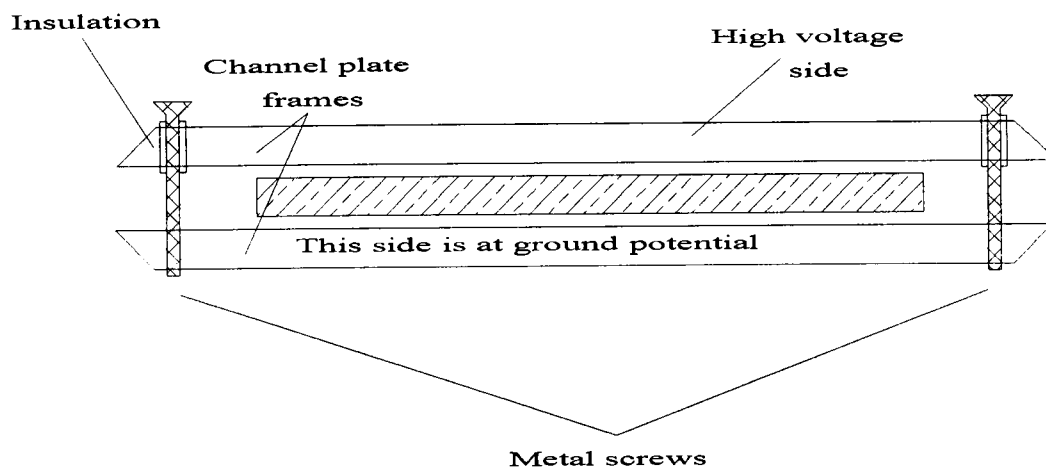


Figure 3.8 Modified Microchannel Plate assembly.

3.6 CHARGE STATE ANALYZER

After exiting the spectrometer, the projectile ions leave the experimental chamber and pass between two parallel polished, aluminum plates of the charge state analyzer. One of these plates has a “bent” section as shown in Figure 3.9. This prevents ions from striking the plate after they have been deflected by an electric field in the region between the plates. Projectile ions enter the charge state analyzer closer to the straight plate, approximately $1/3$ the total distance between the plates. The straight plate is held at a positive voltage, $1/3$ the potential difference between the plates, so that positively charged ions are repelled away from the straight plate. The bent plate is held at a negative voltage equal in magnitude to $2/3$ the potential difference between the plates. The expression for the total deflection of the ion through the length of the

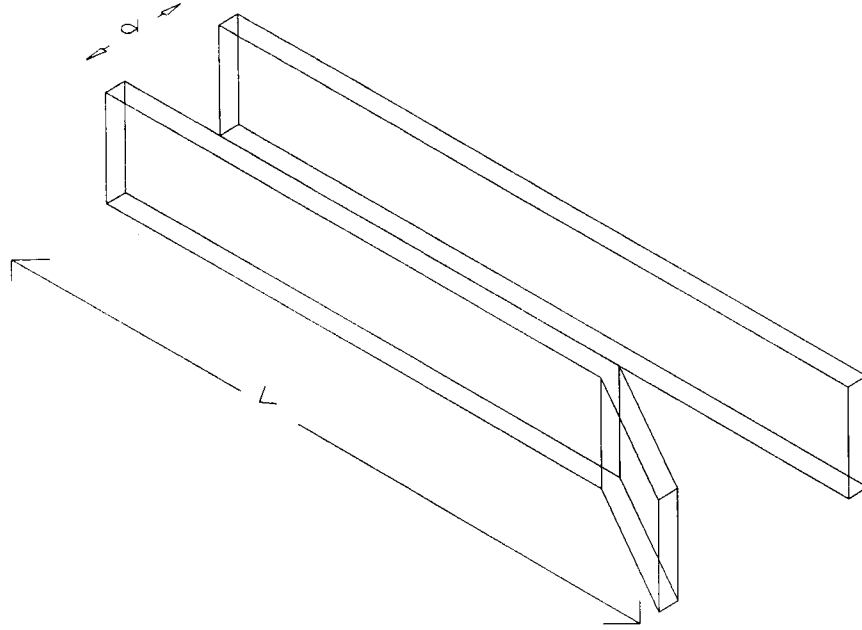


Figure 3.9 Schematic diagram of the charge state analyzer.

charge state analyzer is given by

$$s \approx \frac{10^{-3}}{4} \frac{qV}{AE} \left(\frac{l_1^2}{d_1} + \frac{l_2^2}{d_2} + 2 \frac{l_1 l_2}{d_1} + 2 \frac{l_2 l_3}{d_2} + 2 \frac{l_1 l_3}{d_1} \right) \quad (3.16)$$

where s is the deflection distance given in cm, q is the charge of the ion, V is the potential difference across the plates in kV, A is the nuclear mass number of the projectile, E is the energy of the projectile given in MeV/u, l_1 is the length of the straight sections of the plate, l_2 is the length of the bent section of the plate, l_3 is the distance from the exit end of the charge state analyzer to the ion detector, d_1 is the distance between the straight sections of the plate, and d_2 is the average distance between bent and straight sections of the plates. All of the above distances are given in centimeters.

3.7 ELECTRONICS AND DATA ACQUISITION

PSD Electronics. Electrons ejected from the gas cell with emission angles between 0° and 8° with respect to the beam direction are detected with a position sensitive detector (PSD) located in the focal plane. A schematic diagram of the PSD is shown in Figure 3.10. Position analysis of the electron shower from the micro channel plate onto the resistive anode is done by evaluating

$$X = \frac{Q_B + Q_C}{Q_A + Q_B + Q_C + Q_D} \quad (3.17)$$

and

$$Y = \frac{Q_A + Q_B}{Q_A + Q_B + Q_C + Q_D} \quad (3.18)$$

where the Q_i are the amounts of charge collected at each of the four corners of the anode. Signals from each corner of the resistive anode are the inputs of a preamplifier (Model 24011) manufactured by Quantar Technology. This preamplifier converts the low level pulses into bipolar pulses readable by a Position Computer (Model 2401) also manufactured by Quantar Technology. The Position Computer processes the input signals and outputs analog signals, which can be used to visualize the position on an oscilloscope, and eight bit digital signals for X and Y. This information can be processed, displayed, and stored on a computer. Due to the limited spatial resolution of 30° analyzer caused by the extended source region, the resolution in our experiments is restricted to 64×64 pixels per image.

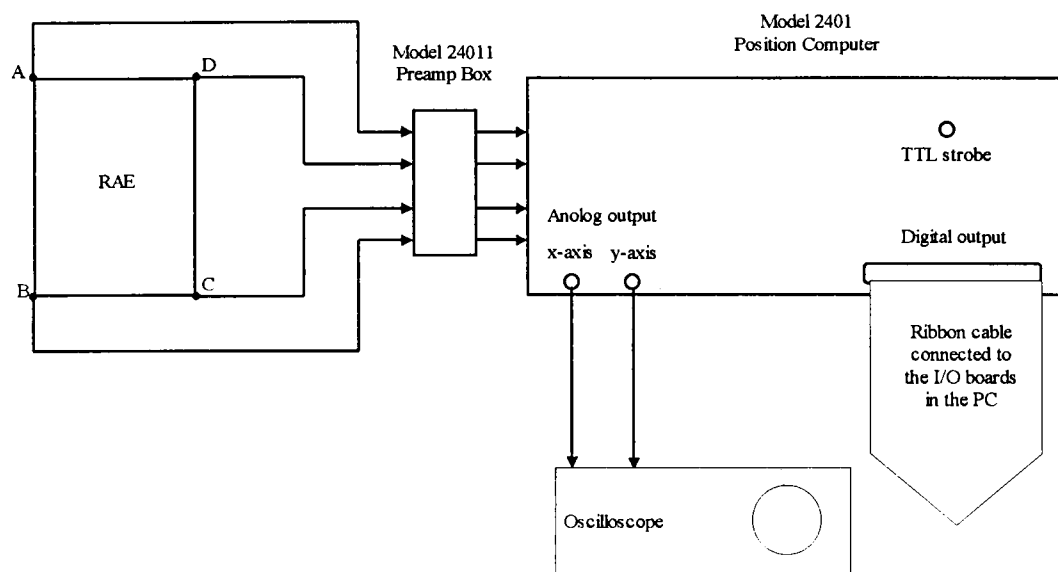


Figure 3.10 Schematic diagram of the PSD electronics.

Non-Coincidence 2D Spectra. Signals from the Position Computer are fed via an I/O board into a personal computer. A data acquisition program monitors the registers of the I/O board and stores the data in an array (non-coincidence array) according to the event's X and Y position.

The total beam current is collected in the Faraday cup located at the end of the beam line. It is electrically connected to a current digitizer which monitors the amount of charge collected in the Faraday cup. For every 10^{-14} Coulomb collected, the digitizer sends a pulse to a Counter/timer. The Counter/timer keeps track of the number of

pulses sent by the Current digitizer. Once it counts a preset number of pulses, it resets itself and sends a channel advance signal which is input into a multi channel scaler (MCS) module of a LeCroy 4500 data acquisition system. Between channel advance signals, the MCS is counting the number of strobe pulses from the Position Computer. The Position Computer produces a strobe pulse for every successfully digitized event. The MCS module stores the number of strobe pulses in 256 channels, from 0 to 255. In channel number 0, it stores the number of times it has scanned the entire range of channels from 1 to 255. The information gathered by the MCS module is used for normalization when the non-coincidence 2D spectra are being acquired.

Coincidence 2D Spectra. Electrons reaching the PSD are detected in coincidence with: 1. the exit charge states of the projectile ion and 2. the charge state of the associated recoil ion. The PC based data acquisition system and the LeCroy 4500 are used together to make coincidence measurements. I will describe the ejected electron-recoil ion coincidence measurements in detail.

The schematic diagram of the electronics setup for acquiring coincidence spectra is shown in Figure 3.11. The data acquisition begins by extracting the electron signal from the Position Computer and the recoil ion signal from the TOF detector.

Information on how the electron signal is extracted and input into the PC is found in the previous section. The TTL strobe signal from the Position Computer is sent to a

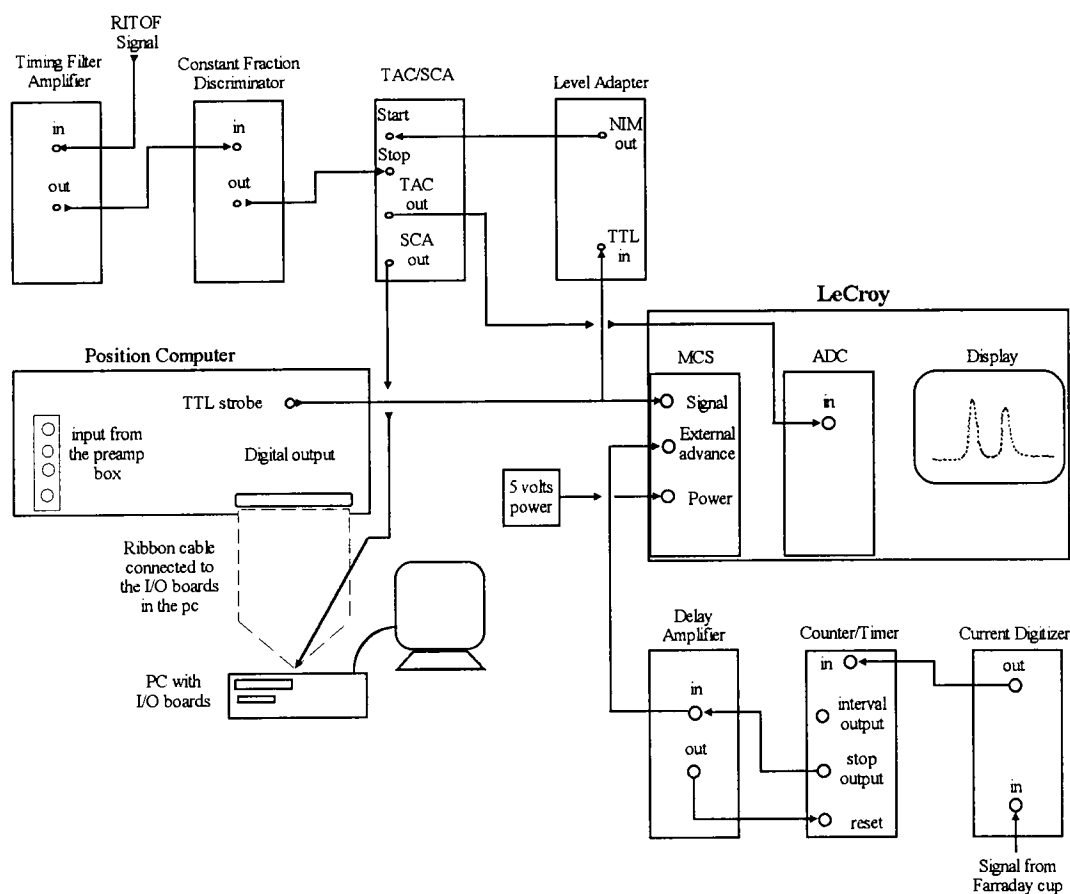


Figure 3.11 Schematic diagram of the electronics setup for the acquiring 2D coincidence spectra.

level adapter where the TTL pulse is converted into a NIM pulse which becomes the start signal for a Time-to-Amplitude Converter (TAC)/Single Channel Analyzer (SCA). The recoil ion signal is capacitively separated from 2200 volts on the copper anode. The pulses have a height of a few mV and a width of a few nanoseconds. They are then fed into an Ortec Model 863 Quad Fast Filter Amplifier. The amplified signal serves as a input for an Ortec Model CF8000 Constant Fraction Discriminator

where the discriminator level is set to block pulses that fall below a certain height. The pulses below a certain height are assumed to come from noise. The discriminated output signal is sent to the TAC/SCA to serve as a stop signal. The TAC/SCA measures the time difference between the start and the stop signal and outputs a pulse between 0 and 10 volts whose height is proportional to the time difference between the start and stop signals. This time difference physically corresponds to the time interval between when the electron strikes the channel plate of the 30° analyzer and when the recoiling ion strikes the channel plate of the TOF. The output of the TAC/SCA is sent to an Analog to Digital Converter (ADC) module of the LeCroy 4500. The ADC module converts the analog voltage signal into a channel number between 1 and 250. A typical ADC spectrum is displayed in Figure 3.12. The peak in the ADC spectrum corresponds to real coincidences, and the approximately straight line background corresponds to random coincidences. Different charge states of the recoil ions appear as different peaks because different charge states take different amounts of time to traverse the RITOF. In order to measure the real coincidences between the forward ejected electrons and different charge states of the recoil ions, the SCA is used. A time window is set around a chosen peak, and every time an event falls within that time window, the SCA sends a signal to the I/O board in the PC. Every time a position signal is sent from the Position Computer to the PC, the data acquisition program checks to see if there was a coincidence between an electron and a recoil ion. In the case that the data acquisition program detects the SCA signal (electron - recoil ion coincidence), it appropriately stores the electron position signal in

either the coincidence array or the non-coincidence array. Our data acquisition program can store the coincidences between electrons and three different charge states of the recoil ion.

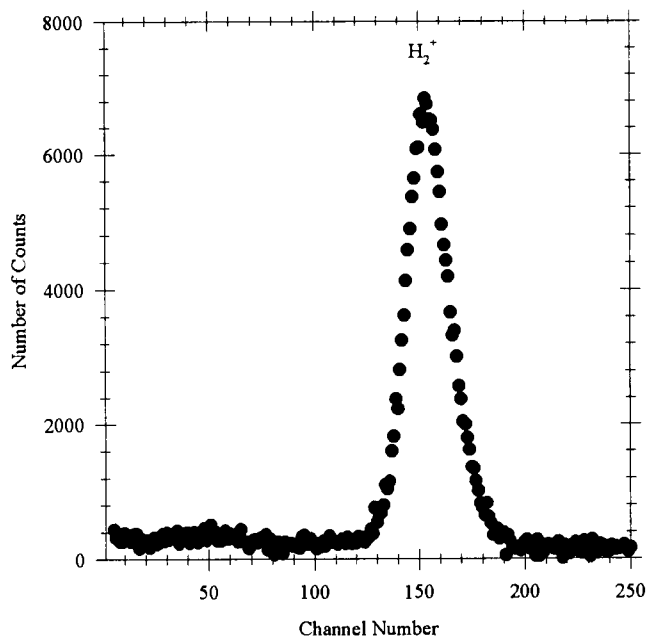


Figure 3.12 ADC spectrum for H_2 recoil ions in coincidence with forward emitted electrons for the C^{2+} on H_2 collision system.

Coincidence Scanned Spectra. One of the features of the Position Computer allows the user to electronically choose a specific area of the anode for data acquisition. Once the small area is chosen, the number of electrons that reach the area can be measured as a function of electron energy without determining their exact emission angle, but integrated over all emission angles that reach this area, by scanning the

analyzer voltage. The electronic setup shown in Figure 3.13 is very similar to what is described in the previous section except for the minor changes described below.

The Counter/timer outputs a channel advance signal. The channel advance signal is used to advance the channel number in the MCS module and to increment the voltage being placed across the 30° analyzer. Every time the voltage is incremented, the energy of the electrons being detected is incremented accordingly. Therefore, each channel number in the MCS module corresponds to a different electron energy. By adjusting the channel number and the voltage across the 30° analyzer, the energy distribution of electrons emitted in the forward direction is scanned and recorded by the MCS module.

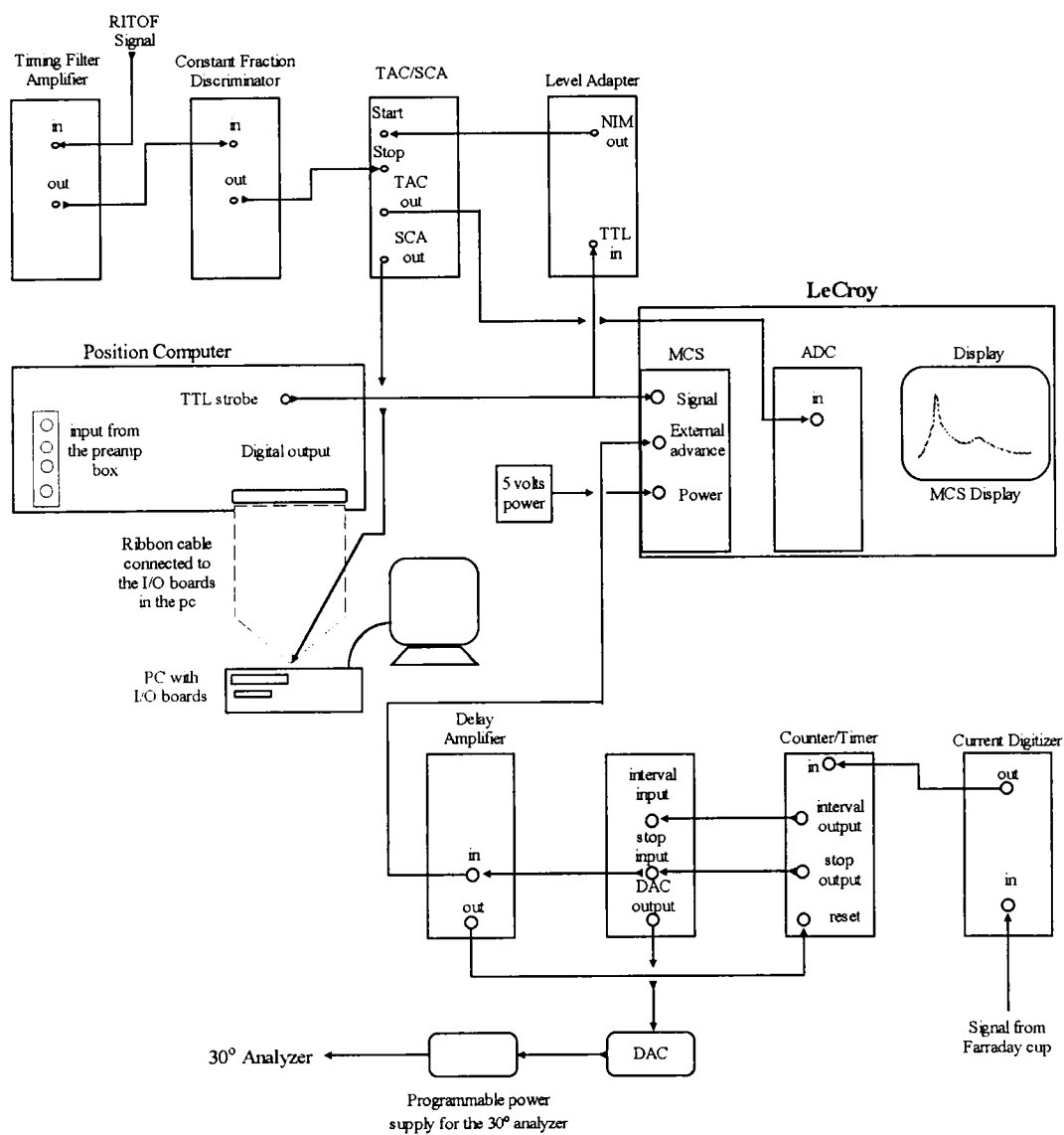


Figure 3.13 Schematic diagram for the electronics setup for the scanning spectra.

CHAPTER 4

ANALYSIS

4.1 DATA ANALYSIS

The 30° parallel plate electrostatic analyzer is used to measure the energy and angular distribution of electrons ejected within 0° to 8° with respect to the beam direction for the 0.5 MeV/u C²⁺ onto H₂ collision system. The energy of the measured electrons ranges from 0 to 1450 eV. The spectrum of electrons emitted near the forward direction for the above mentioned collision system is measured over this entire range. This includes cusp, Auger, and binary encounter electrons. These measurements are made in coincidence with selected exit charge states of the projectile ions and selected charge states of the recoil ions. The spectrum is normalized to the total amount of charge collected in the Faraday cup or to the number of ions with a selected charge state counted by the ion detector located at the end of the beam line. From these measurements, the doubly differential cross section of electron production for different electronic processes is obtained.

4.2 BACKGROUND AND RANDOM SUBTRACTION

An important aspect of the data analysis is background subtraction. Background is introduced into the electron emission spectra from several sources during an experiment. One possible source is the collision of projectile ions with the gas-cell, the

apertures, or the grids. In our experiment, this kind of background is negligible since a well collimated beam is obtained from the accelerator and very good alignment of the beam with respect to the entrance and the exit apertures of the spectrometer is obtained. In order to reduce the background contribution due to the electrons colliding with the grids in the analyzer, special handmade grids are used which reduce the background significantly. Background counts are still not negligible on the part of the detector which intercepts low energy electrons since this section of the detector directly "looks into" the analyzer. However, when electron spectra are measured in coincidence with either the recoil ion charge state or exit charge state of the projectile ions, then this background is significantly reduced.

The coincidence spectra contain contributions from random coincidences. The number of random coincidences is determined from the corresponding ADC spectrum. A typical ADC spectrum, as shown in Figure 3.12, shows the number of recoil ions detected after the corresponding electron detection versus the channel number which is proportional to the time it takes the recoil ion to traverse the distance within the RITOF spectrometer. The large peak in the ADC spectrum corresponds to the recoil ion charge state of H_2^+ . It rests on an approximately straight line background of random coincidences which are caused by electrons and recoil ions from different collisions starting and stopping the TAC, respectively. The energy and angular spectrum of electrons measured in coincidence with recoil ions of a certain charge state contains all events that fall into the window set with the SCA around the

corresponding recoil ion peak in the ADC spectrum. The contribution due to random events is found from a straight line fit to the ADC spectrum from which all channels corresponding to recoil ion peaks have been removed. The corresponding spectrum of electrons detected independent of any coincidence requirement is normalized to one, multiplied by the total number of random coincidences, and subtracted from the raw coincidence spectrum channel by channel. An underlying assumption in performing the random subtraction as described above is that the shape of the random coincidence spectrum is the same as the shape of the non-coincidence spectrum.

4.3 SIMULATION PROGRAMS

In order to obtain the doubly differential cross section from the experimentally measured spectrum, the properties of the measuring apparatus, i.e. the 30° parallel plate electrostatic energy analyzer, must be understood in detail. We need to know its energy and angular resolution, its transmission function, and the solid angle subtended by each pixel of the position sensitive detector. To find these properties, a computer simulation program has been written which traces individual electrons from the gas cell through the spectrometer to the detector.

This simulation program consists of two computer programs written in the Visual Basic language, SIMULATE.EXE (Appendix D) and SORT.EXE (Appendix E). The SIMULATE.EXE program simulates how an electron with a given velocity will evolve in time under the influence of Newton's laws of motion, inside the analyzer with

deflecting voltage V , and reach its final position on the focal plane. The SORT.EXE program is an auxiliary program to SIMULATE.EXE. It sorts the events from the data file generated by SIMULATE.EXE according to the energy and the final position on the position sensitive detector.

The simulation program SIMULATE.EXE uses three different frames of references which are shown in Figure 3.4: the Gas-cell frame of reference (Region I), the Earth-plate frame of reference (Region II), and the Focal plane frame of reference (Region III). The Gas-cell frame of reference is rotated by -30° from the Earth-plate frame of reference, and the Focal plane frame of reference is rotated 10.9° from the Earth-plate frame of reference. The program incorporates the exact dimensions of all the apertures and slits and the exact locations of the gas-cell, the high voltage plate, the focal plane, etc.

In the gas cell, SIMULATE.EXE assigns each electron random spatial components X_o , Y_o and Z_o in the intersection region of ion beam and target gas and random velocity components V_{xo} , V_{yo} and V_{zo} . The values assigned to the velocity components depend only on the analyzer voltage chosen by the user. After these assignments, the trajectory of the electron is calculated according to Newton's laws of motion.

In Region I, the electric field is zero, and therefore, the electron's trajectory is not deflected. As the electron's trajectory traverses Region I, the program tests that the

electron does not strike any walls or apertures. If this should happen, the program reverts back to the beginning where it starts assigning random position and velocity components to a new electron.

If the electron successfully traverses Region I, it's position is found at the boundary between Regions I and II. A frame transformation then follows from the gas-cell frame of reference to the earth-plate frame of reference for the position and velocity coordinates.

In Region II, the electron moves in the presence of an electric field and accelerates. The program checks whether an electron is deflected enough to stay within Region II or whether it travels beyond the limits of the high voltage plate and thus, exits Region II. If the electron is deflected towards the earth plate, the program determines whether the electron will strike at the boundary between Regions II and III. A frame transformation from the Earth-plate coordinate system to the Focal plane coordinate system then follows.

Region III is a field free region, and the electron follows a straight line trajectory. If the electron does not strike any walls and successfully travels to the focal plane, there are two options. If there is no bias voltage, it again follows a straight line trajectory to the channel plate, else the trajectory evolves under the influence of the electric field due to the bias voltage. The bias voltage is the voltage at the "front" of the channel

plate due to which very low energy electrons are repelled and less background is introduced into the spectrum. The bias voltage is another quantity that the user is required to input before the execution of the code begins. The bias voltage is taken into account because it alters the final position of the electron on the PSD.

Once the electron reaches the channel plate, the final positions X_{final} , Z_{final} and the velocities $V_{x-final}$, $V_{y-final}$, $V_{z-final}$ are determined (the magnitude of the final velocity components is the same as that of the initial velocity components) and stored in appropriate arrays. The program repeats the entire process until 4,000,000 successful events are stored; a successful event consists of an electron born in the gas cell traveling successfully to the channel plate. The event counter in the program keeps track of the total number of random events generated in order to find the efficiency of the spectrometer. In this simulation program, approximately 65% of the randomly generated events successfully reach the detector. In other words, there are in the neighborhood of 6,153,000 random events generated during the course of this simulation.

This program runs in a reasonable amount of time on a desktop computer. On a 133 MHz Pentium desktop computer, the execution time is two and a half hours for 4,000,000 successful events. The motivation behind choosing 4,000,000 successful events is the following. 4,000,000 events evenly distributed over 4096 channel of the "detector" yield approximately 977 events per channel; the statistical error introduced

due to this number of counts is $\frac{1}{\sqrt{977}} = 0.032$, or approximately 3.2%. By having more counts, the statistical error is not significantly decreased, but the computing time and the required storage space go up linearly.

The program SORT.EXE sorts the data generated by SIMULATE.EXE. Before the execution of SORT.EXE begins, the user has to input three parameters: the number of events to be sorted, the full path name of the data file to be sorted, and the name of the directory where the output files should be saved.

SORT.EXE generates six output files which are shown in the flow diagram in Figure 4.1. These output files are inputs for different programs; the program EXTCSXN.EXE (Appendix F) uses one of the output files to obtain cross sections from the experimental data. The commercial program SIGMA PLOT generates plots of the number of events vs. pixel (i,j) as shown in Figure 4.2. One of the output files is used for energy calibration of the PSD. Figure 4.3 shows the plot of energy vs. pixel (i,j) at an analyzer voltage of -353 volts.

4.4 CROSS SECTIONS

To extract doubly differential electron production cross sections from the energy and angular distributions obtained experimentally, certain quantities have to be known: the effective length of the gas-cell l , the number of target atoms per cm^3 per mTorr n_0 ,

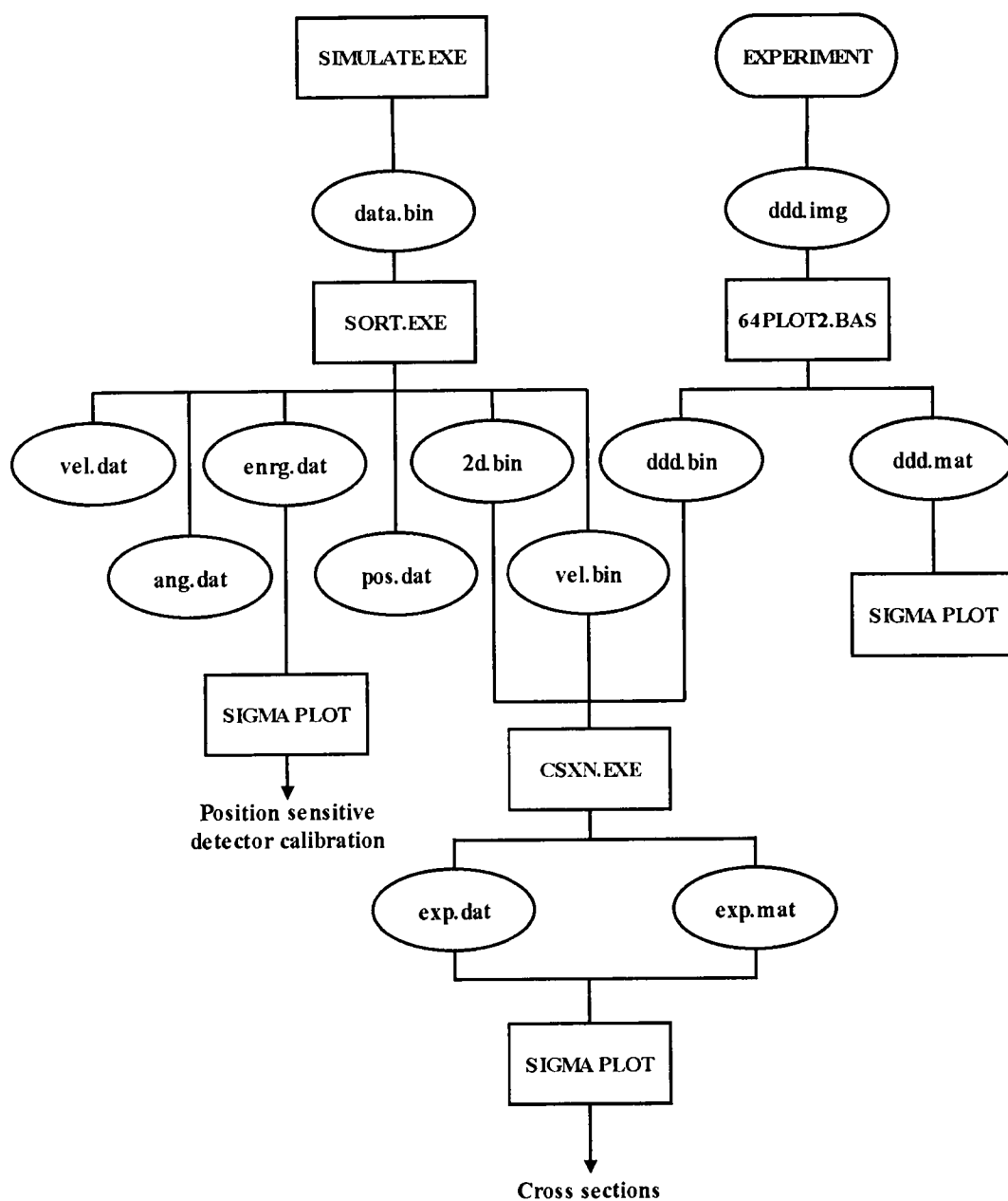


Figure 4.1 Flowchart showing the relationships between the simulation programs and their output files. Key: rectangles = programs, ellipses = output files.

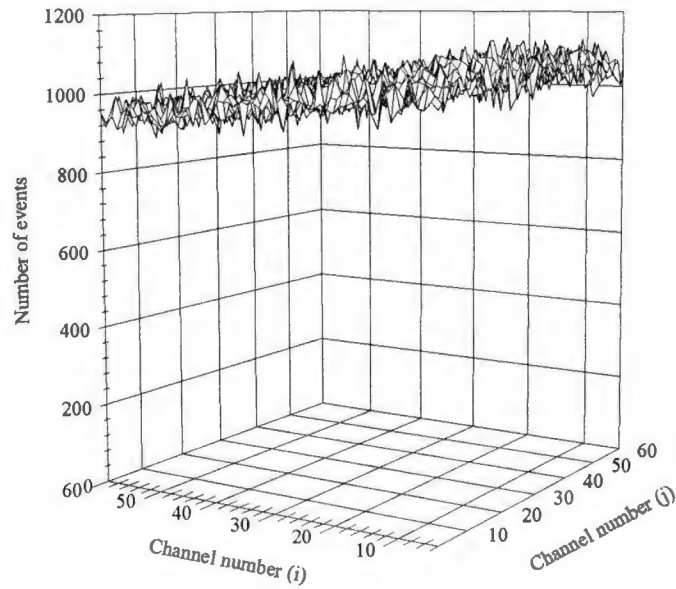


Figure 4.2 Plot of number of events on the position sensitive detector vs. pixel (i,j) generated by the simulation program.

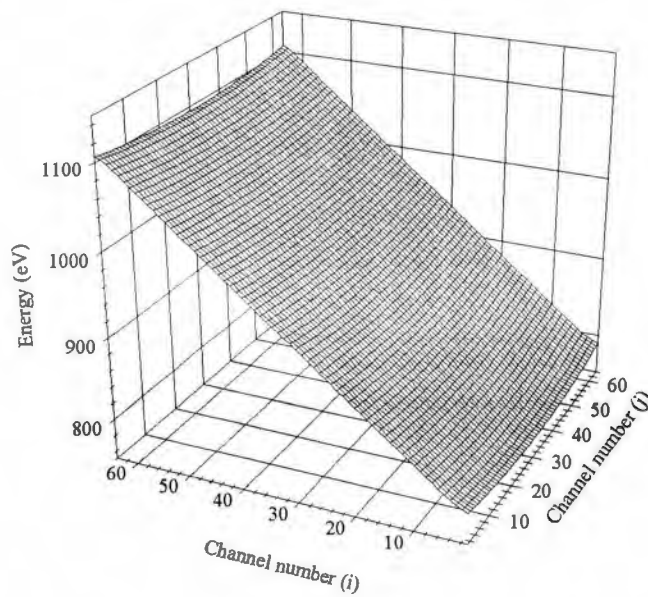


Figure 4.3 Graph of energy vs. pixel (i,j) on the position sensitive detector at the analyzer voltage of -353 volts.

the transmission function of the 30° parallel plate analyzer, and the number of incident projectile ions. n_0 is found from the ideal gas law; the effective gas cell length l is estimated by adding the diameter of the exit aperture to the actual gas cell length. The transmission function of the 30° parallel plate analyzer is obtained by analyzing the output of the simulation program.

In the simulation program, the number of electrons emitted from the gas-cell that successfully reach pixel (i , j) of the detector when the analyzer voltage is V is given by

$$N_{ij} = N \int_{\Delta v_x} \int_{\Delta v_y} \int_{\Delta v_z} P_{ij}(\mathbf{v}) T_{ij}(\mathbf{v}) dv_x dv_y dv_z \quad (4.1)$$

Here N is the total number of trials, $P_{ij}(\mathbf{v}) dv_x dv_y dv_z$ is the probability that an electron in the gas-cell is born within a velocity volume element $d^3v = dv_x dv_y dv_z$, and $T_{ij}(\mathbf{v})$ is the transmission function of the 30° parallel plate analyzer. In the simulation program, the probability that an event is generated within the entire velocity volume V_v is given by

$$\int_{\Delta v_x} \int_{\Delta v_y} \int_{\Delta v_z} P(\mathbf{v}) dv_x dv_y dv_z = 1 \quad (4.2)$$

where $V_v = \int_{\Delta v_x} \int_{\Delta v_y} \int_{\Delta v_z} dv_x dv_y dv_z = \Delta v_x \Delta v_y \Delta v_z$ and $P_{ij}(\mathbf{v})$ is a constant since we generate a uniform distribution in velocity space. Thus, the above expression becomes

$$P_{ij}(\mathbf{v}) V_v = 1$$

or

$$P_{ij}(\mathbf{v}) = \frac{1}{V_v} \quad (4.3)$$

Therefore, Equation 4.1 which gives the number of electrons that reach the detector

can be rewritten as

$$N_{ij} = \frac{N}{V_v} \int_{\Delta v_x} \int_{\Delta v_y} \int_{\Delta v_z} T_{ij}(v) dv_x dv_y dv_z$$

or

$$\int_{\Delta v_x} \int_{\Delta v_y} \int_{\Delta v_z} T_{ij}(v) dv_x dv_y dv_z = \frac{V_v N_{ij}}{N} \quad (4.4)$$

In the experiment, the number of electrons $N_{ij \text{ exp}}(v)$ reaching pixel (i,j) with energy $E = \frac{1}{2}mv^2$ is given by

$$N_{ij \text{ exp}}(v) = N_p \iiint P_{ij \text{ exp}}(v) T_{ij}(v) \text{eff}(v) dv_x dv_y dv_z \quad (4.5)$$

where N_p is the number of projectile ions passing through the gas-cell. $P_{ij \text{ exp}}(v) d^3v$ is the probability that in the ion-atom collision an electron is produced within the velocity volume d^3v about the velocity v , and $\text{eff}(v)$ is the electron detection efficiency. If $P_{ij \text{ exp}}(v)$ and $\text{eff}(v)$ do not vary much over the velocity volume accepted by pixel (i,j), they can be taken out of the integral; thus, the above expression can be rewritten as

$$N_{ij \text{ exp}}(v) = N_p P_{ij \text{ exp}}(v) \text{eff}(v) \int_{v_x} \int_{v_y} \int_{v_z} T_{ij}(v) dv_x dv_y dv_z \quad (4.6)$$

Making use of Equation 4.4, it can be rewritten as

$$N_{ij \text{ exp}}(v) = N_p P_{ij \text{ exp}}(v) \text{eff}(v) V_v \frac{N_{ij}}{N} \quad (4.7)$$

where we can define $\frac{N_{ij}}{N} = \varepsilon$.

Therefore,

$$P_{ij \text{ exp}}(v) = \frac{N_{ij \text{ exp}}(v)}{N_p V_v \varepsilon \text{eff}(v)} \quad (4.8)$$

The expression that relates the cross section $\frac{d\sigma}{dv}$ and $P_{ij\text{exp}}(v)$ is

$$\frac{d\sigma}{dv} = \frac{P_{ij\text{exp}}(v)}{n_0 p l} = \frac{N_{ij\text{exp}}(v)}{N_p V_v \varepsilon n_0 p l_{\text{eff}}(v)} \quad (4.9)$$

where n_0 is the number of target atoms per cm^3 per mTorr, p is the pressure in the gas-cell in mTorr, and l is the effective gas-cell length in cm. Since the analyzer used in the experiment is an energy analyzer, the cross section is measured as a function of energy. The formula that relates $\frac{d\sigma}{dv}$ and $\frac{d^2\sigma}{dE d\Omega}$ is given by

$$\frac{d\sigma}{dv} v^2 dv d\Omega = \frac{d^2\sigma}{dE d\Omega} dE d\Omega = \frac{d^2\sigma}{dE d\Omega} m v dv d\Omega \quad (4.10)$$

Therefore,

$$\frac{d^2\sigma}{dE d\Omega} = \frac{d\sigma}{dv} \frac{v}{m} \quad (4.11)$$

which can be rewritten as

$$\left(\frac{d^2\sigma}{dE d\Omega} \right)_{ij} = \frac{N_{ij\text{exp}}(v) V_{ij}}{N_p n_0 p l \varepsilon_{ij} V_v m_{\text{eff}}(v)} \quad (4.12)$$

where $\left(\frac{d^2\sigma}{dE d\Omega} \right)_{ij}$ is the doubly differential cross section measured on the (i, j) pixel of the 64×64 matrix.

$N_{ij\text{exp}}(v)$ is the random subtracted electron spectrum obtained from the experiment. V_{ij} is the matrix of velocities obtained from the simulation program at an analyzer voltage that corresponds to the experimentally obtained electron spectrum. ε_{ij} is the ratio of the electrons that strike each of the 4096 bins divided by the total number of trials; this information is obtained from the simulation program. V_v is the velocity space volume subtended by the detector at an analyzer voltage that corresponds to the

experimentally obtained electron spectrum.

Equation 4.12 finds the doubly differential cross section from the number of electrons reaching each pixel of the 64×64 matrix. When only a small area of the position sensitive detector is used and the analyzer voltage is scanned, certain changes need to be made in the way we compute the cross section. We use

$$V_v \cong v^2 \Delta v \Delta \Omega = \frac{v}{m} m v \Delta v \Delta \Omega = \frac{v}{m} \Delta E \Delta \Omega \quad (4.13)$$

By substituting the above expression for V_v into Equation 4.12, it becomes

$$\frac{d^2 \sigma}{dE d\Omega} = \frac{N_{\text{exp}}(v)}{N_p \Delta E \Delta \Omega \epsilon n_0 p \text{eff}(v)} \quad (4.14)$$

where ΔE , $\Delta \Omega$, and ϵ are obtained from the simulation program for the appropriate “area” of the position sensitive detector that was used for data acquisition.

$\text{eff}(v)$ is the electron detection efficiency. If the electrons are detected independent of any coincidence requirements, $\text{eff}(v)$ is the detection efficiency of the channel plate multiplied by the transmission probability of the electrons through the grids (99%). If the electrons are detected in coincidence with the recoil ion charge states, the recoil ion detection efficiency must also be included. It is determined by using Ar gas and assuming that every time a cusp electron is produced a recoil ion is also produced.

The analyzer voltage is set so that the cusp electrons are detected in coincidence with the recoil ion charge states. All the recoil ions are summed up and divided by the total number of detected cusp electrons. This quantity equals the recoil ion detection

efficiency. In this experiment, the recoil ion detection efficiency is found to be $1.01\% \pm 0.05\%$.

Relative errors in the DDCS are mainly due to the statistical fluctuations and fluctuations of the target gas pressure in the gas-cell. Statistical errors always increase after background subtraction. Absolute errors are due to errors in the effective length of the gas-cell, the channel plate electron detection efficiency, and the recoil ion detection efficiency. The following values are used to determine the uncertainties in DDCS: $l = 1.2 \pm 0.12$ cm, $\frac{\Delta E}{E} = 0.36 \pm 0.00$, $\Delta\Omega = 0.039$ sr, and $eff = 50\% \pm 10\%$. All errors are propagated quadratically. Absolute errors contribute approximately 25% to the total error in the DDCS.

The position sensitive detector is electronically divided into 64×64 bins. This allows 4096 different positions where electrons can strike the detector. Thus, the solid angle subtended by each pixel in the 2D spectrum is approximately $\frac{\Omega}{4096}$ sr where Ω is the total solid angle subtended by the position sensitive detector.

For our one dimensional spectra, only a small portion of the position sensitive detector was used for data acquisition when the electron energy was scanned. The solid angle subtended per data point is $n \frac{\Omega}{4096}$ where n is the number of pixels available for data acquisition. It is clear that in these spectra the solid angle per data point is larger than

in the 2D spectra.

If the electron emission spectrum is sharply peaked, then the measured doubly differential cross section $\frac{d^2\sigma}{dEd\Omega}$ is highly dependent on the solid angle subtended by the detector used in the measurement. The experimental doubly differential cross section is obtained by averaging the number of counts reaching the detector over the solid angle subtended by the detector. For a sharp peak in a spectrum, this translates into more averaging around the peak for a larger solid angle than a smaller one. Thus, for a sharp peak in the spectrum, the DDCS obtained from our 2D spectra will be higher than the DDCS obtained from our 1D scanned spectra.

CHAPTER 5

RESULTS AND DISCUSSION

The energy and angular distribution of electrons ejected near the forward direction is measured for the 0.5 MeV/u C²⁺ on H₂ collision system. The detected electrons range in energy from 0 eV to 1450 eV. Cusp electrons are detected at approximately 274 eV, and Auger and binary encounter electrons are detected at approximately 1000 eV. The electron yields are obtained in coincidence with the exit charge states 2+, 3+, and 4+ of the projectile ions. From these yields, the doubly-differential cross section $\frac{d^2\sigma}{dEd\Omega}$ for electron production is computed. Electron yields are also obtained in coincidence with recoil ion charge state H₂⁺, and the doubly-differential cross section for this process is computed. The measured cross section for binary encounter electron production is compared with the theoretical predictions of the impulse approximation.

Figure 5.1 shows the energy dependence of the doubly differential cross section multiplied by energy, $\frac{d^2\sigma}{dEd\Omega}E$, for electron emission within a cone of 2° about the forward direction. The error bars in the figure indicate one standard deviation relative errors. This cross section was measured independent of any coincidence requirement. We can clearly identify the cusp at ~ 274 eV and the BEE peak at ~ 1000 eV.

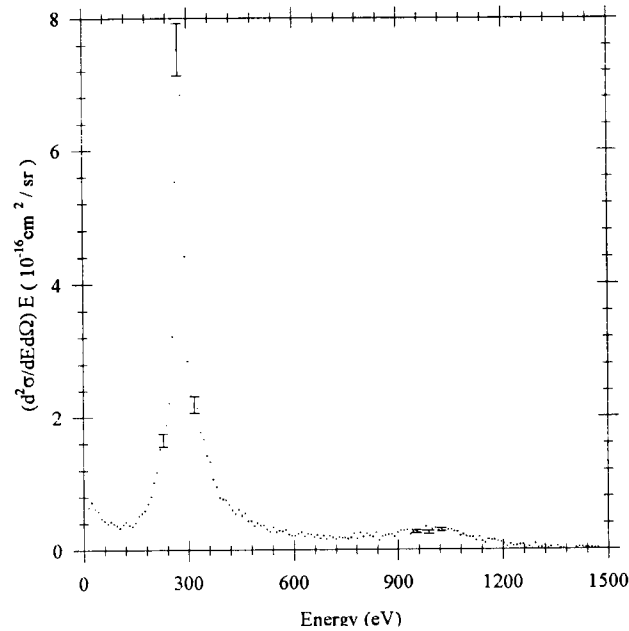


Figure 5.1 DDCS, multiplied by energy, for electron emission at $\sim 0^\circ$ with respect to the beam direction and averaged over an angular range of $\sim 2^\circ$, for 0.5 MeV/u C^{2+} on H_2 .

5.1 CUSP ELECTRON SPECTRA

Figures 5.2 and 5.3 show the doubly differential cross section for cusp electron production in coincidence with single ionization of the projectile. Figure 5.2 shows the energy dependence of the cross section averaged over an angular range of $\sim 2^\circ$ about the forward direction with an energy resolution of $\frac{\Delta E}{E} = 2\%$. Figure 5.3 shows the energy as well as angular dependence of the cross section. The angular resolution here is 0.1° , and the energy resolution is $\frac{\Delta E}{E} = 1\%$. Figures 5.4 and 5.5 show the doubly differential cross section for cusp electron production in coincidence with double ionization of the projectile. No cusp electrons are detected in coincidence with

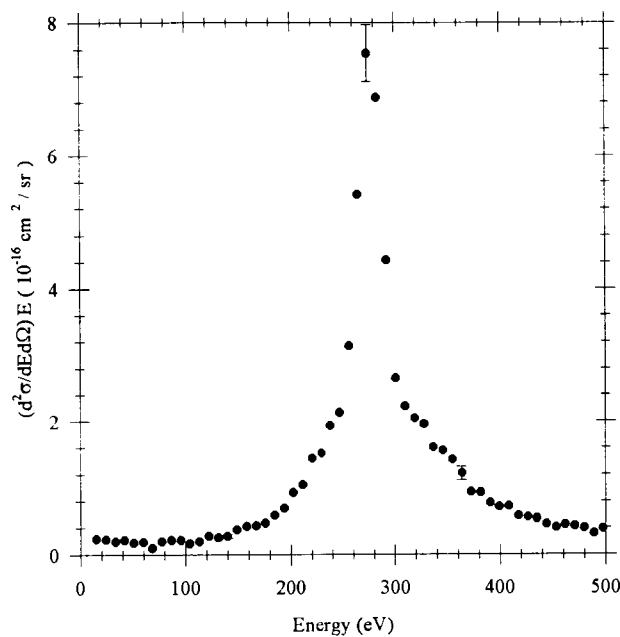


Figure 5.2 DDCS, multiplied by energy, for cusp electron production at $\sim 0^\circ$ with respect to the beam direction and averaged over an angular range of $\sim 2^\circ$, in coincidence with the projectile ion exit charge state of $3+$ for $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 .

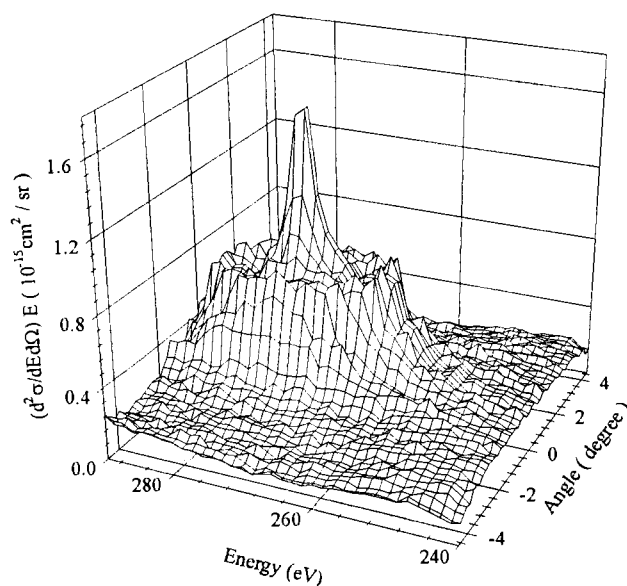


Figure 5.3 Energy and angular dependence of the DDCS multiplied by energy for cusp electron production within 0° to 4° with respect to the beam direction for $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 . This spectrum is measured in coincidence with the projectile ion exit charge state of $3+$.

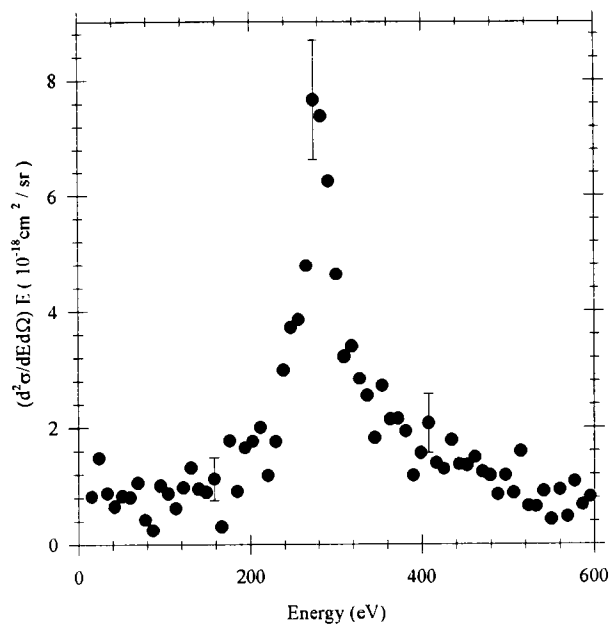


Figure 5.4 DDCS, multiplied by energy, for cusp electron production at $\sim 0^\circ$ with respect to the beam direction and averaged over an angular range of $\sim 2^\circ$, in coincidence with the projectile ion exit charge state of $4+$ for $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 .

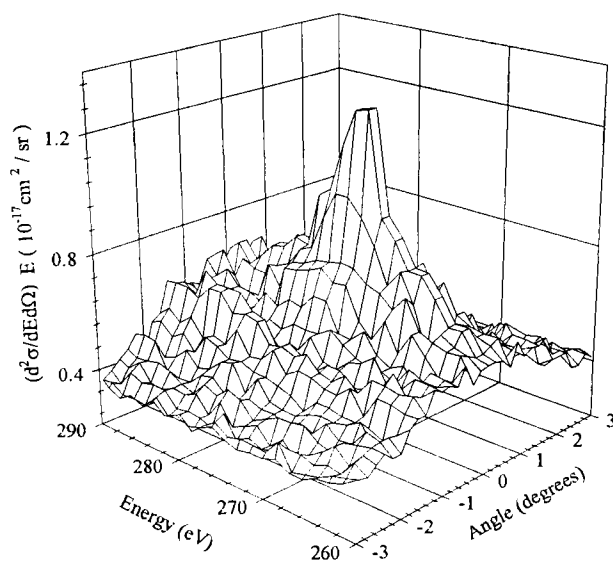


Figure 5.5 Energy and angular dependence of the DDCS, multiplied by energy, for cusp electron production within 0° to 4° with respect to the beam direction for $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 . This spectrum is measured in coincidence with the projectile ion exit charge state of $4+$.

the projectile exit charge states 5+ and 6+. All the cusp electrons are detected in coincidence with the projectile exit charge states 3+ and 4+, and the sum of these two coincidence cross sections adds up to the total cusp electron production cross section. This is verified by comparing the cusp electron production cross sections in Figures 5.2 and 5.4 with the cusp electron production cross section in Figure 5.1. The measurements of cusp electron production in coincidence with the projectile exit charge state indicate that cusp electrons are entirely due to the electron loss process.

Figures 5.2 and 5.4 show that the electron production cross section for producing cusp electrons in coincidence with projectile exit charge state C^{3+} is approximately 100 times larger than the cross section for producing cusp electrons in coincidence with projectile exit charge state of C^{4+} . Cusp electrons are almost entirely produced in projectile single ionization processes. For 0.5 MeV/u C^{2+} projectiles colliding with H_2 , single ionization dominates projectile ionization. It is much easier to ionize one projectile electron than it is to ionize two projectile electrons.

Figure 5.6 shows the energy and angular distribution of cusp electrons detected in coincidence with H_2^+ recoil ions. The angular resolution is 0.1° , and the energy resolution is $\frac{\Delta E}{E} = 1\%$. Measurements did not yield any cusp electrons in coincidence with H^+ recoil ions. The cross section for producing cusp electrons in coincidence with H_2^+ recoil ions is nearly the same as the total cusp cross section. This indicates

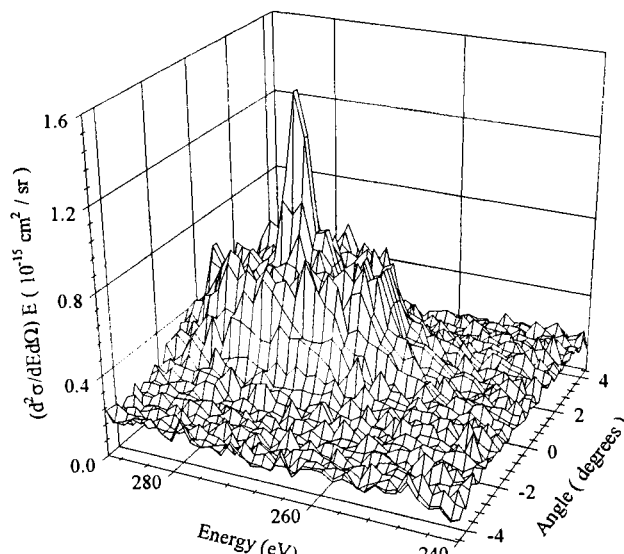


Figure 5.6 Energy and angular dependence of the DDCS, multiplied by energy, for cusp electron production within 0° to 4° with respect to the beam direction for 0.5 MeV/u C^{2+} on H_2 . This spectrum is measured in coincidence with the recoil ion charge state H_2^+ .

that nearly all the cusp electrons are produced in collisions in which both the target and the projectile are each singly ionized.

Figures 5.2 and 5.3 both show the cross sections for the production of cusp electrons in coincidence with the projectile exit charge state C^{3+} . In Figure 5.2, the cross section is averaged over an angular range of $\sim 2^\circ$, and in Figure 5.3, it is averaged over $\sim 0.1^\circ$. The main reason for the differences in the magnitude of the electron production cross sections shown in the two figures is the large difference in the angular ranges.

Measured cusp cross sections are highly dependent on both the energy resolution and

the solid angle subtended by the detector since the cusp is sharply peaked in energy as well as in angle. Therefore, the cross section measured with better energy and angular resolution shown in Figure 5.3 is noticeably higher at the cusp energy than the cross section measured with poorer resolution shown in Figure 5.2. If a moving average of the middle of the 2D spectrum of cusp electrons in Figure 5.5 is used to compute the DDCS averaged over the same solid angle subtended by the detector in the scanned spectrum, the cross sections obtained from the 2D spectrum and the scanned spectrum agree very well, as shown in Figure 5.7.

The BEE peak is a broad feature in the electron emission spectrum in energy as well as angle. The measured cross section for BEE production will therefore only depend weakly on the energy and angular resolution of the detector.

The structures appearing in the wings of the cusp in Figure 5.8, and as a ring surrounding the cusp in Figure 5.3, are due to the production of low energy projectile Auger electrons. Single-electron excitation or ionization cannot lead to these auto ionization lines. Double-electron excitation is responsible. The lines originate from $1s^2 2p\ n\ell$ projectile auto ionization states. In the projectile rest frame the energy of the ring surrounding the cusp is shown in Figure 5.3 is 0.133 eV. This corresponds to the transition $1s^2 2p\ n\ell - (1s^2 2s) + e^- (kl')$. The approximate energy of the ejected electron in the projectile frame is calculated using the formula $E \approx E_\infty - \frac{(13.6 \cdot q^2)}{(n-\mu)^2}$ where E_∞ is

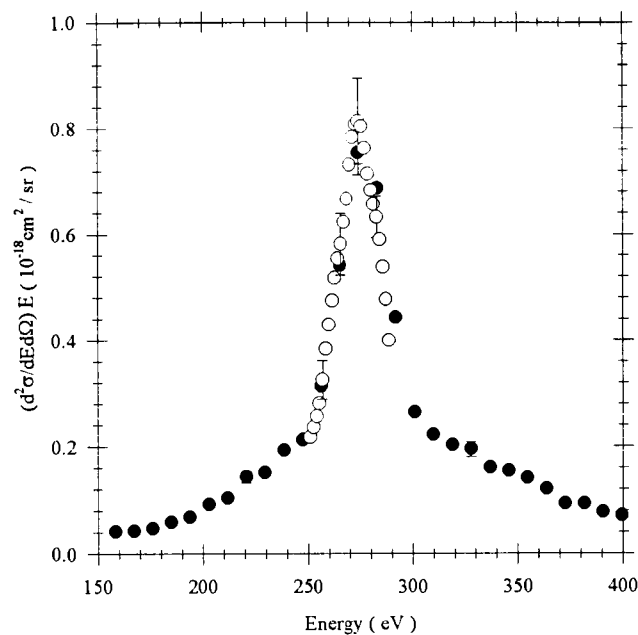


Figure 5.7 Comparison of the cross section shown in Figure 5.4 (filled circles) with the run averaged cross section from Figure 5.5 (open circles).

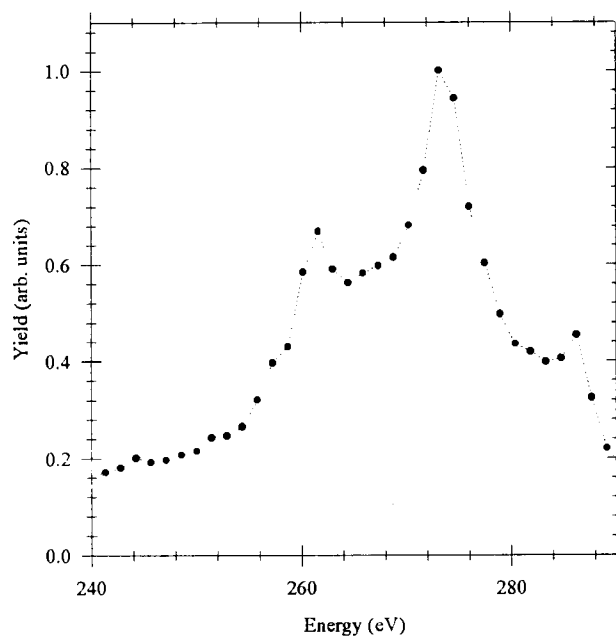


Figure 5.8 Yield of forward emitted cusp electrons for 0.5 MeV/u C^{2+} on H_2 .

the energy in eV of the series limit, q is the charge of the residual ion, n is the principal quantum number of outermost excited electron, and u is the quantum defect. E_∞ is taken from atomic energy-level tables (Bashkin and Stoner 1975) and is 8.00 eV for C^{3+} . With a quantum defect of $u \cong 0.1$, we conclude that $n = 4$. The atomic energy level tables show that some, but not all, l values and coupling schemes for the $n = 4$ level can lead to autoionization. Transitions with $n = 3$ are energetically forbidden. Auger lines from $n = 5$ are expected at $E \cong 3$ eV in the projectile rest frame. They cannot be seen in our spectrum because, at the analyzer voltage of -97.4 volts, our high resolution spectrum does not extend far enough.

High resolution measurements of the cross section for cusp electron production were motivated by two previous experiments. One of these experiments (Wig 1995) investigated the significance of the projectile electron-target electron interaction in the production of cusp electrons. It looked for signs of this electron-electron interaction in the cusp yields and the cusp shapes as a function of recoil ion and projectile ion charge state for 3 MeV C^{1+} projectiles on Ar targets. While the yields of the cusp electrons as a function of recoil ion and projectile ion exit charge state suggest that the electron-electron interaction is important in cusp electron production for this collision system, the cusp shapes were found to be independent of recoil ion charge state. In a different experiment however, cusp shapes seem to depend on projectile incident charge states (Sanders *et al* 1995). Sanders *et al* investigated the cusp shape and yield

independent of any coincidence requirement for 0.5 MeV/u neutral carbon, C^{1+} , and C^{2+} projectiles colliding with H_2 . For C^{2+} projectiles, the cusp seemed significantly narrower than for C^{0+} and C^{1+} projectiles as seen in Figure 5.9. This could be a sign of electron-electron interaction which is expected to contribute significantly to the cusp electron yield for C^{0+} and C^{1+} but not for C^{2+} projectiles. We repeated our high resolution measurements of the cusp electron yield for 0.5 MeV/u C^{1+} projectiles on H_2 . Figure 5.10 shows the spectrum measured with C^{1+} projectiles. Figure 5.11 and 5.12 compare cuts through these 2D spectra measured with different incident charge states of the projectile. The cut in Figure 5.11 is made at 0° along the energy axis, and the cut in Figure 5.12 is made at the cusp energy of 273.4 eV along the angle axis.

The cuts are plotted versus the velocity in the projectile frame.

The most significant difference in the spectra measured with C^{1+} and C^{2+} projectiles is the intensity and the position of the Auger lines. For C^{1+} projectiles, the Auger lines result from $1s^2 2s 2p \rightarrow nl$ transitions, and their energy in the projectile frame is expected at $E \approx E_\infty - \frac{(13.6 \cdot q^2)}{(n-\mu)^2}$ with $E_\infty = 6.5$ eV and $q = 2$. Transitions with $n = 3$ are allowed and are observed at 0.336 and 0.654 eV. The quantum defect is ~ 0.1 . The transitions with $n = 4$ are expected at ~ 2.92 eV and are not observed in our spectrum.

The underlying cusp shape measured with C^{1+} and C^{2+} projectile seems to be the same within statistical error. No narrowing of the C^{2+} cusp is observed. When we overlay

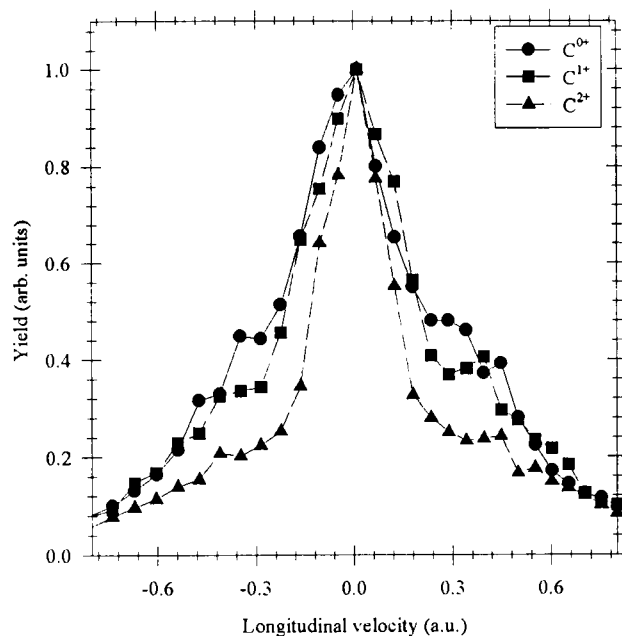


Figure 5.9 Yield of forward emitted cusp electrons for 0.5 MeV/u C^{0+} (filled circles), C^{1+} (filled squares), and C^{2+} (filled triangles) on H_2 (from Sanders *et al* 1995).

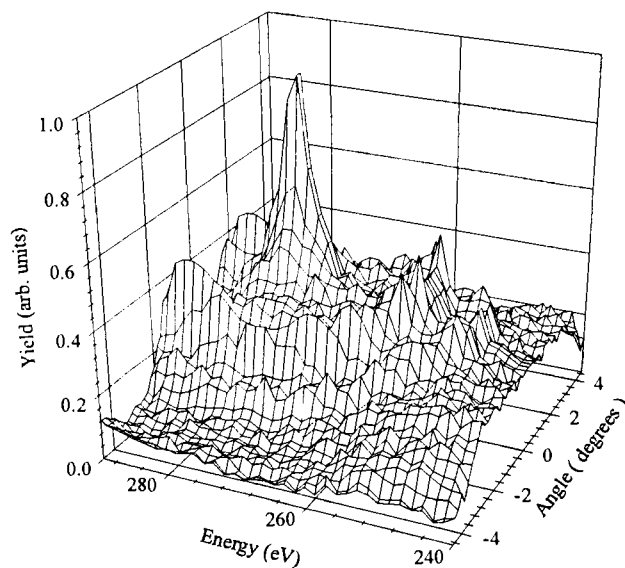


Figure 5.10 Energy and angular distribution of forward emitted cusp electrons within 0° and 4° for 0.5 MeV/u C^{1+} on H_2 .

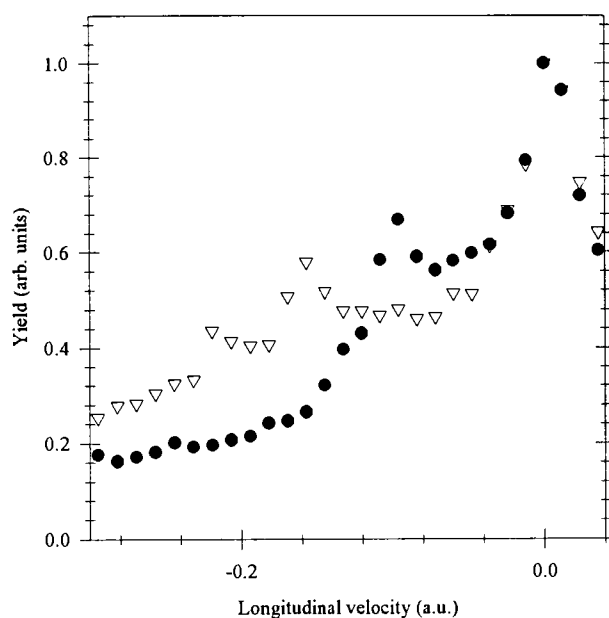


Figure 5.11 Comparison of cuts from Figures 5.3 (filled circles) and 5.10 (open triangles) made at 0° along the energy axis. The yields are plotted vs. the longitudinal velocity (parallel to the beam axis) in the projectile frame.

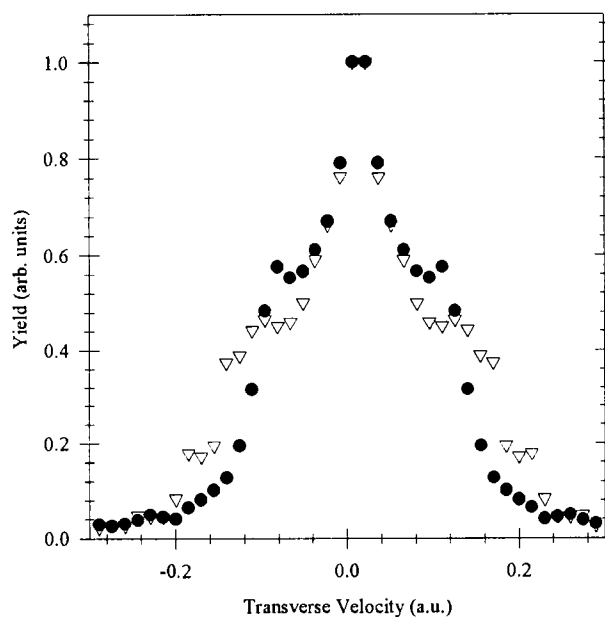


Figure 5.12 Comparison of cuts from Figures 5.3 (filled circles) and 5.10 made at the cusp energy of 274.3 eV along the angle axis. The yields are plotted vs. the transverse velocity (perpendicular to the beam axis) in the projectile frame.

the spectrum measured by Sanders *et al* with our spectrum, we see the reason of the apparent narrowing seen in their spectrum in Figure 5.13. The resolution of their apparatus was not good enough to resolve the very low energy projectile Auger lines. The different positions and intensities of these lines in the spectra measured with C^{1+} and C^{2+} lead to the apparent difference in width. The Auger lines observed in the spectrum measured by Sanders *et al* appear at much higher energy and are due to transitions with $n = 4$.

5.2 AUGER ELECTRON SPECTRA

Figure 5.14 shows the cross section for producing high energy projectile Auger electrons in coincidence with projectiles with exit charge state C^{4+} . The Auger electron production cross section in Figure 5.14 is measured with an angular resolution of 0.1° , and the energy resolution is 1%. The electrons detected at ~ 1000 eV in coincidence with C^{4+} are projectile KLL Auger electrons from Li-like $1s\ 2s\ 2l$ configurations. In the ion-atom collision, a projectile K shell electron is excited or ionized. The K-shell vacancy is filled by an electron from the L-shell, and a second L-shell electron is ejected. This leaves a He-like projectile ion. The intensity of Auger electron lines from Li-like Carbon has been studied (Deveney *et al* 1995). Deveney *et al* compared experimental results with theoretical predictions using hidden crossing techniques and conclude that Auger electron intensity variations can be used to probe collision dynamics. We are planning a collaboration with Deveney to analyze the structure of the Li-like Ar KLL lines measured in our experiment.

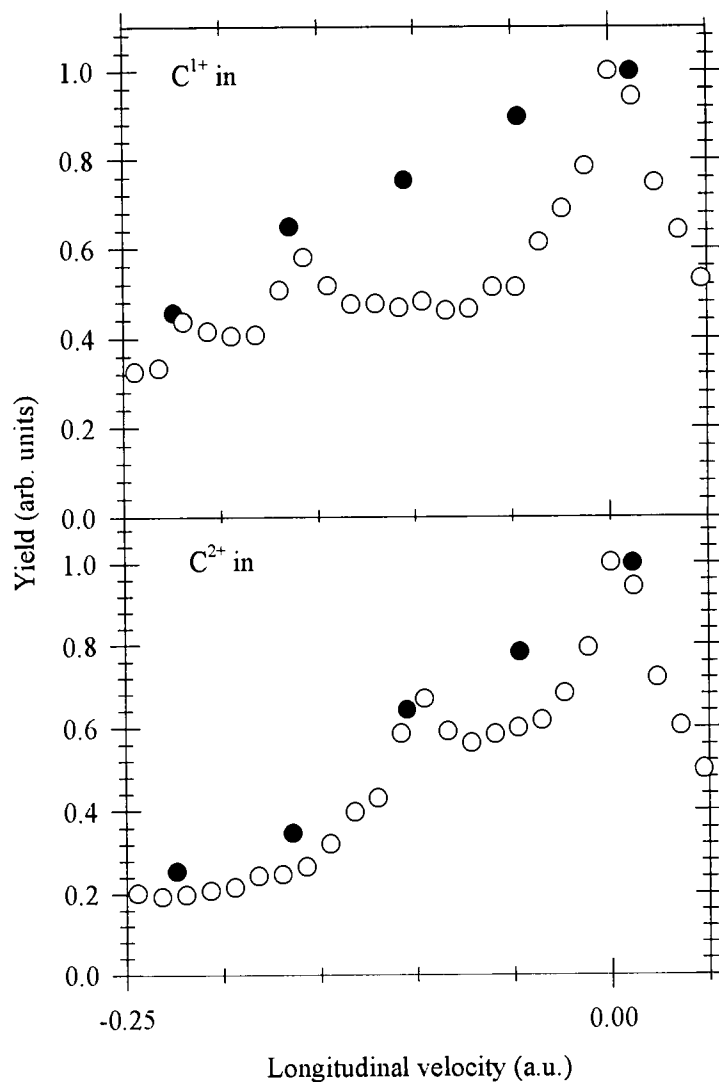


Figure 5.13 Comparison of the yields of cusp electrons emitted at 0° with respect to the beam direction. The upper spectra are measured with 0.5 MeV/u C^{1+} on H_2 , and the lower spectra are measured with 0.5 MeV/u C^{2+} on H_2 . Filled circles represent the data from Figure 5.9, and open circles represent the data from Figure 5.11.

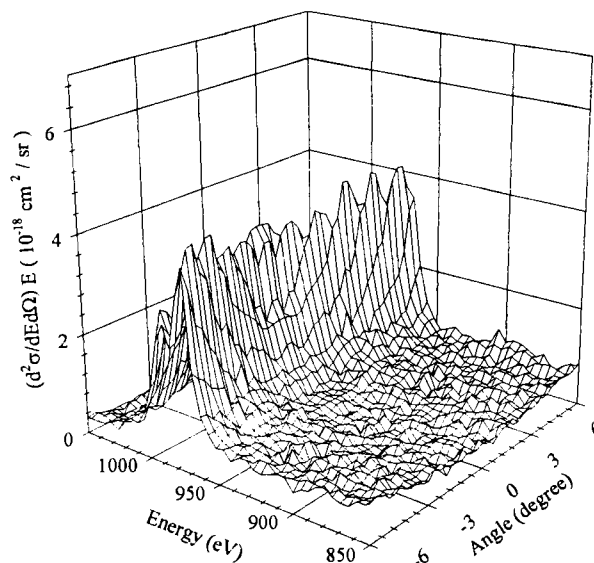


Figure 5.14 Energy and angular distribution of the DDCS, multiplied by energy, of high energy projectile Auger electrons measured in coincidence with the projectile ion exit charge state of 4+ for 0.5 MeV/u C^{2+} on H_2 .

5.3 BINARY ENCOUNTER ELECTRON SPECTRA

Figure 5.15 shows the energy distribution of BE electrons detected within 4° of the forward direction in coincidence with C^{2+} projectile ions. The energy resolution is $\frac{\Delta E}{E} = 2\%$. No binary encounter electrons are detected in coincidence with any other exit charge state of the projectile, i.e. 3+, 4+, 5+, and 6+. The binary encounter electron production cross section measured in coincidence with the projectile exit charge state C^{2+} has nearly the same magnitude as the total binary encounter electron production cross section shown in Figure 5.16. The BE electron is a target electron which is ionized in a close collision with the projectile core. The projectile core

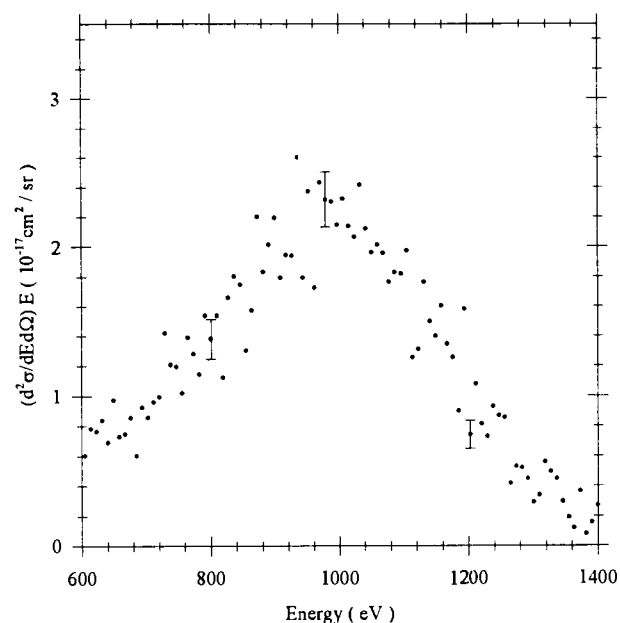


Figure 5.15 DDCS, multiplied by energy, for binary encounter electrons emitted near the forward direction and averaged over $\sim 4^\circ$ for 0.5 MeV/u C^{2+} on H_2 . These electrons are measured in coincidence with the projectile ion exit charge state of $2+$.

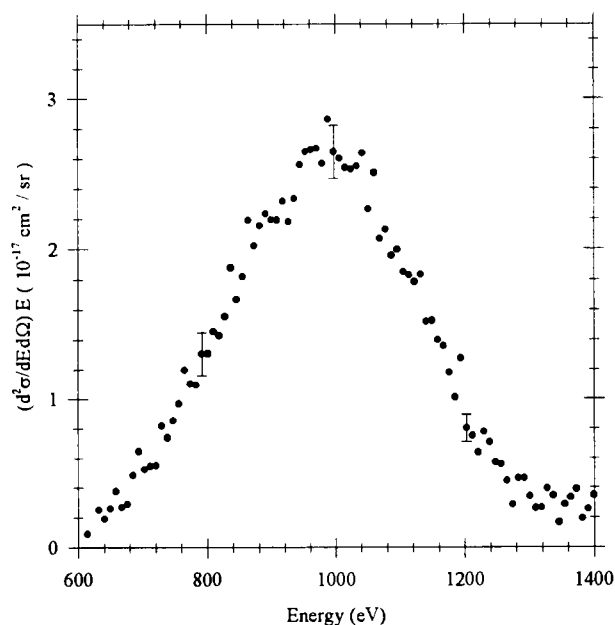


Figure 5.16 DDCS, multiplied by energy, for binary encounter electrons emitted near the forward direction and averaged over $\sim 4^\circ$ for 0.5 MeV/u C^{2+} on H_2 . These electrons are measured independent of any coincidence requirements.

evidently remains intact during this collision. This suggests that while the impact parameter between projectile core and target electron is small, the impact parameter between projectile core and target core is large.

Figures 5.17 and 5.18 show the energy and angular distribution of BE electrons in coincidence with H_2^+ target recoil ions with energy resolution of $\frac{\Delta E}{E} = 1\%$ and angular resolution of 0.1° . These figures are shown from two different perspectives. Binary encounter electrons are only detected in coincidence with H_2^+ recoil ions. Again, the binary encounter electron production cross section measured in coincidence with H_2^+ is nearly the same as the total binary encounter electron production cross section in Figure 5.16. When the BE electron is ionized in a close collision with the projectile core, the rest of the target remains intact. Once again, we conclude that the impact parameter between projectile core and the target nucleus is large.

Figure 5.19 compares the binary encounter electron production cross section measured in coincidence with projectile exit charge state 2^+ and the cross section measured in coincidence with the recoil ion charge state H_2^+ . These cross sections agree well with each other. Measurements that are obtained in coincidence with the recoil ion charge states do not distinguish between the exit charge states of the projectile ions. Thus, those measurements also include a small contribution due to the Auger electrons that are detected in coincidence with projectile exit charge state of C^{4+} . The cross section for producing these Auger electrons is 10 times smaller than the BEE production cross

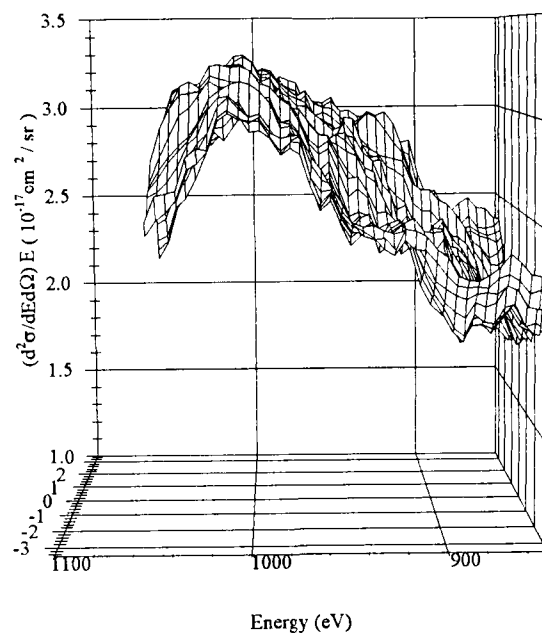


Figure 5.17 Energy and angular distribution of the DDCS, multiplied by energy, of binary encounter electrons measured in coincidence with the recoil ion charge state of H_2^+ for 0.5 MeV/u C^{2+} on H_2 (shown from the perspective of the energy axis).

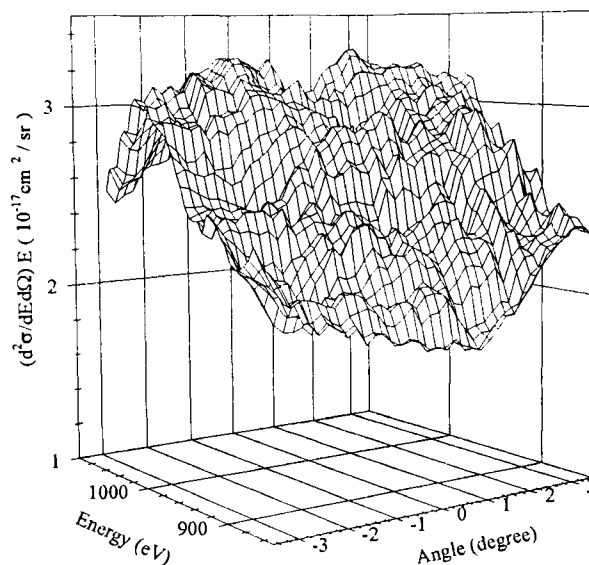


Figure 5.18 Energy and angular distribution of the DDCS, multiplied by energy, of binary encounter electrons measured in coincidence with the recoil ion charge state of H_2^+ for 0.5 MeV/u C^{2+} on H_2 (shown from the perspective of the energy and angle axes).

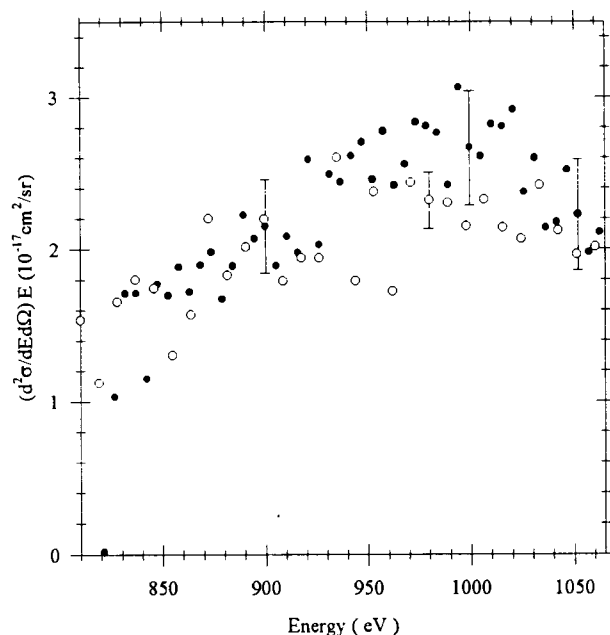


Figure 5.19 Comparison of the cross sections for binary encounter electron production measured in coincidence with projectile ion exit charge state of 2+ (open circles) and recoil ion charge state H_2^+ (filled circles) for 0.5 MeV/u C^{2+} on H_2 .

section, and thus, adding it does not alter the binary encounter electron production cross section significantly.

Our coincidence measurements yield nearly complete kinematic information about the collision partners when BE electrons are produced in 0.5 MeV/u C^{2+} on H_2 collisions. This is a great aid in understanding the collision dynamics. Our results show that for binary encounter electron production in our collision system, the charge state of the projectile remains unchanged and the target is singly ionized. Since binary encounter electrons emerge from a head on “hard collision” between target electron and

projectile ion, multiple ionization of the target as well as the projectile ions might be expected; yet, this is not observed in our experiment. Binary encounter electron production requires only a close collision between the target electron and projectile nucleus and not necessarily a close collision between the two nuclei. It is evident from our results that as far as BEE production is concerned, the C^{2+} on H_2 collision system is a nearly ideal three body system in which the three well separated collision partners are the target core, the target electron, and the screened projectile nucleus. For such a collision system, the impulse approximation is expected to make accurate predictions.

Our impulse approximation calculations were performed for binary encounter electron production cross section in the collision of 0.5 MeV/u C^{2+} onto H_2 . For the ESM on-shell approximation, the results of the calculation of the BEE production cross section are shown in Figure 2.5. Figure 5.20 compares the calculated and the measured BEE production cross section as a function of electron energy and emission angle for electron production near the forward direction within 0° and 3.5° . The magnitude of the calculated cross section agrees well with the magnitude of the experimentally obtained cross section. Figure 2.6 compares the measured cross section at 0° with the cross sections calculated using the ESM and using OSA 1. Both the ESM and the OSA 1 calculations shift the BEE peak toward higher energy by approximately 40 eV ($\sim 4\%$). ESM calculations by Sanders *et al* for various projectiles with $q = 7$ colliding with hydrogen also show that the ESM shifts the BEE peak towards higher energy when compared with experimental data. The ESM

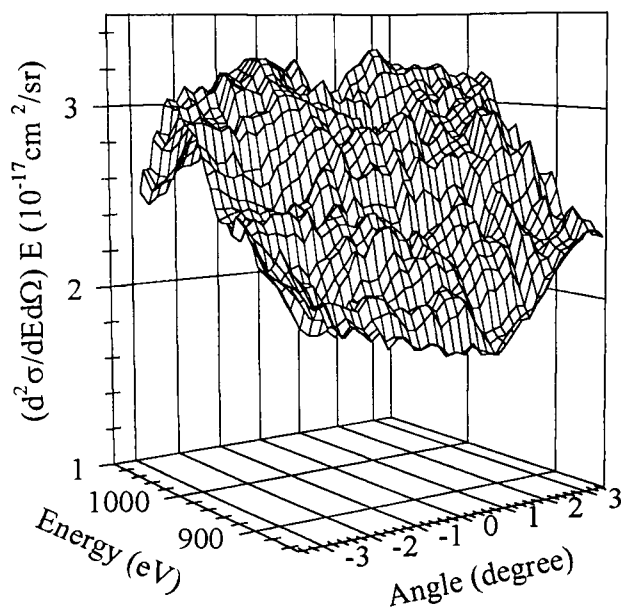
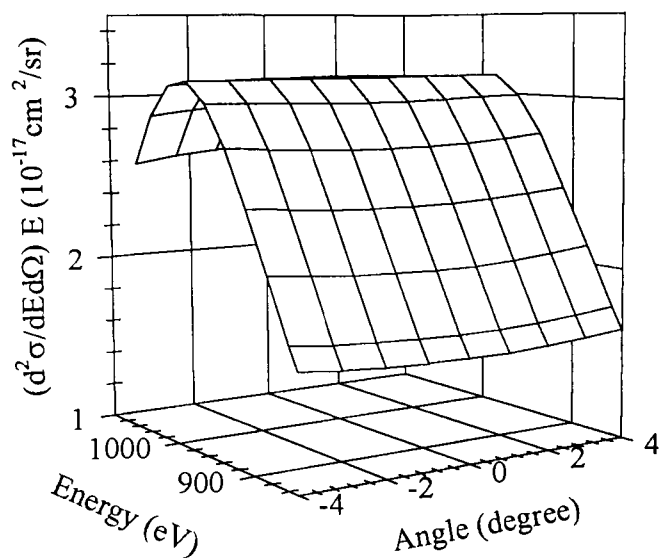


Figure 5.20 Comparison of the DDCS, multiplied by energy, for binary encounter electron production for 0.5 MeV/u C^{2+} on H_2 . The upper spectrum shows the results of the ESM calculations, and the lower spectrum shows the measured production DDCS.

predicts relative peak positions and trends quite well but produces a shift for all projectiles. If we subtract 40 eV from the energy axis of both the ESM and OSA 1 calculations, then the magnitude and shape of the calculated and experimentally obtained BEE production cross sections agree quite well as shown in Figure 5.21.

Figures 5.18 and 5.22 show a “dip” in the angular distribution of binary encounter electrons right at zero degrees with respect to the beam direction. We suspect that the dip is an experimental artifact, but it has been difficult to pinpoint the mechanism. The calculations do not show any such structure near the forward direction in the binary

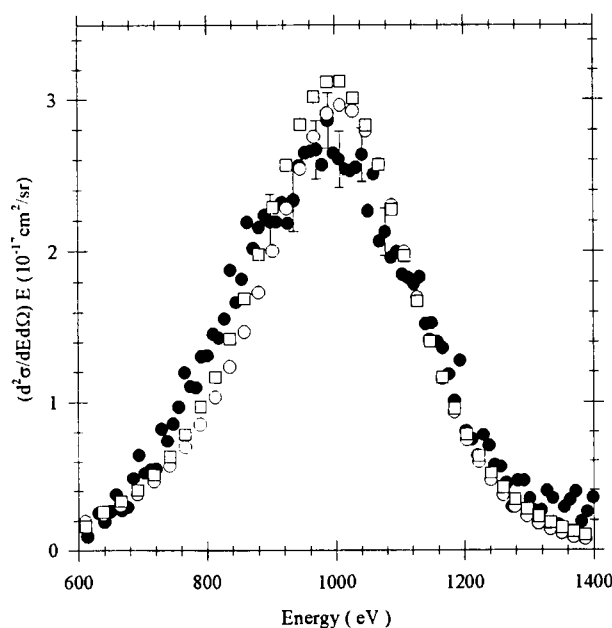


Figure 5.21 Comparison of the measured and calculated DDCS for binary encounter electron production at 0° for 0.5 MeV/u C^{2+} on H_2 . Open squares represent ESM calculations, open circles represent OSA 1 calculations, and filled circles represent measured cross sections. The energy scale for the theoretical cross sections has been shifted by 40 eV.

encounter electron production cross section.

One possibility is that the construction of the gas cell or the analyzer reduces the electron detection efficiency of the apparatus at 0° compared to larger angles. This is not unreasonable since the analyzer has holes to let the ion beam exit which can lead to distortions of the electric field inside the analyzer. From this explanation, we would then expect to observe a similar dip in the spectrum of Auger electrons shown in Figure 5.14 since these electrons are also detected with ~ 1000 eV and follow the same trajectories through the analyzer. No such "dip" is observed near zero degrees in the spectrum of Auger electrons as can be clearly seen in a contour plot shown in Figure 5.23. Due to low recoil ion detection efficiency, count rates are low, and the data acquisition time for the spectrum shown in Figure 5.18 is long. Maybe the dip is still a consequence of insufficient statistics. Further experiments are needed to determine the origin of this structure.

5.4 SUMMARY

For the $0.5 \text{ MeV/u } \text{C}^{2+}$ on H_2 collision system, we measured the cross section for producing cusp electrons, Li-like KLL Auger electrons, and binary encounter electrons.

Cusp electrons are almost exclusively produced in collisions which involve single ionization of both projectile and target. Binary encounter electrons, on the other hand,

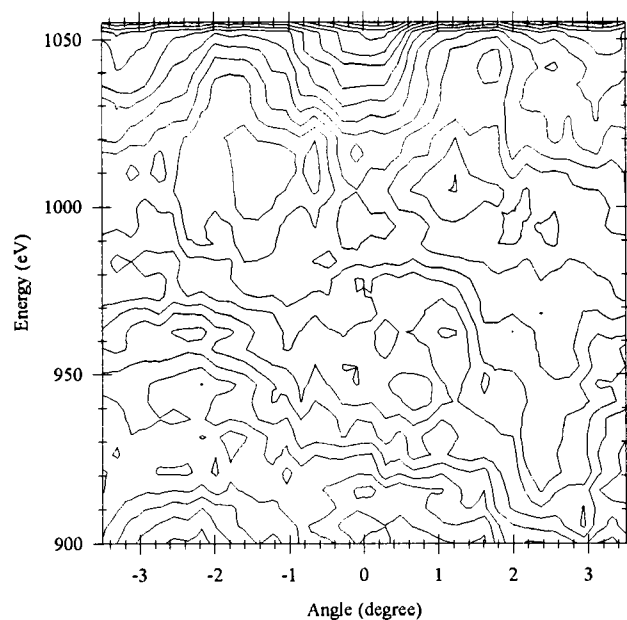


Figure 5.22 Contour plot of the yield of binary encounter electrons detected in coincidence with the recoil ion charge state H_2^+ for 0.5 MeV/u C^{2+} on H_2 .

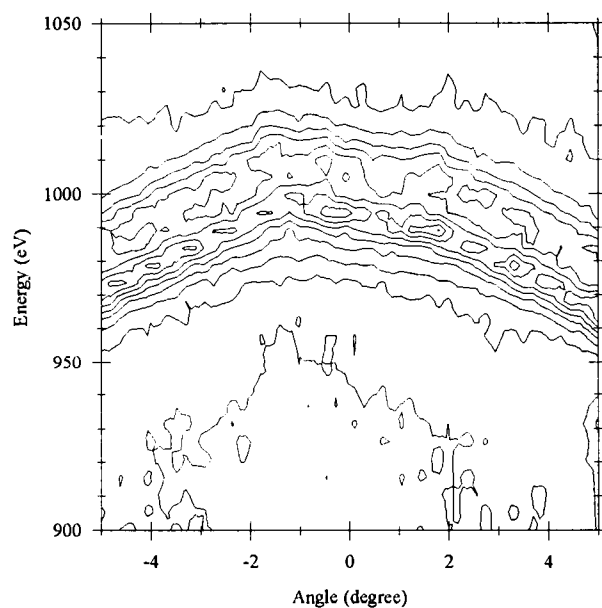


Figure 5.23 Contour plot of the yield of projectile Auger electrons detected in coincidence with the projectile ion exit charge state of 4+ for 0.5 MeV/u C^{2+} on H_2 .

are produced in collisions in which the projectile remains intact and does not change charge. The only electron which is ionized in the collision is the BE electron itself. We can therefore confidently model BEE production as a 3-body collision process. The impulse approximation reproduces the magnitude and the shape of the BEE peak quite well but shifts the position of the BEE peak by $\sim 4\%$ toward higher energy. This shift seems to be a consequence of the IA itself and not a consequence of the particular on-shell approximation used.

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APPENDICES

APPENDICES

Appendix A contains the code for the computer program DELTA.BAS that calculates the phase shift for a modified Coulomb potential as a function of energy and the angular momentum. Appendix B contains the code for the computer program CROSS.BAS that calculates the cross section for free electrons scattering off C^{2+} . Appendix C contains the code for the computer program OSAH2ANG.BAS that calculates the binary encounter electron production cross section as a function of energy and angle. The above programs are written in the Quick Basic computer programming language. Figure 2.4 shows the relationships between these programs and their output files.

Appendix D contains the 30° parallel plate analyzer simulation program SIMULATE.EXE. Appendix E contains the sorting program SORT.EXE that sorts through the output file of SIMULATE.EXE. Appendix F contains the program EXTCSXN.EXE that computes the cross section from the experimentally obtained electron spectra. The above programs are written in the Visual Basic computer programming language. Figure 4.1 shows the relationships between these programs and their output files.

APPENDIX A

DELTA.BAS

'DELTA.BAS for a hydrogenic ion

'This program calculates the phase shift δ_l for a modified
'Coulomb potential $-Ze^2/r + V(r)$ as a function of the energy e
'and the angular momentum l .

CLS

pi = 3.14159: hbar = 7.62003:

rmax = 5: dr = .000002

nr = rmax / dr

DIM psi1 AS DOUBLE, psi2 AS DOUBLE, psi3 AS DOUBLE, ps AS DOUBLE

'pick the behavior at large distances

z = 2

z1 = z + 4

FOR e = 500 TO 1000 STEP 50

k2 = 2 * e / hbar: k = SQR(k2)

FOR l% = 0 TO 20

'routine to integrate the Schroedinger equation using the Numerov method

'for the Coulomb potential

cons = dr * dr / (hbar * 6)

ll = l% * (l% + 1) * hbar / 2

psi1 = 0: psi2 = (l% + 1) * 10 * dr ^ (l% + 1)

r = dr

v = -z * 14.3998 / r

v = v + ll / (r * r)

kim1 = cons * (e - v)

r = 2 * dr

v = -z * 14.3998 / r

v = v + ll / (r * r)

ki = cons * (e - v)

FOR i = 2 TO nr - 1

r = (i + 1) * dr

v = -z * 14.3998 / r

v = v + ll / (r * r)

kip1 = cons * (e - v)

ps = ((2 - 10 * ki) * psi2 - (1 + kim1) * psi1)

```

        psi3 = ps / (1 + kip1)
        kim1 = ki: ki = kip1: psi1 = psi2: psi2 = psi3
    NEXT i
    u1 = psi3
    r1 = r
    FOR i = nr TO nr + 9999
        r = (i + 1) * dr
        v = -z * 14.3998 / r
        v = v + ll / (r * r)
        kip1 = cons * (e - v)
        ps = ((2 - 10 * ki) * psi2 - (1 + kim1) * psi1)
        psi3 = ps / (1 + kip1)
        kim1 = ki: ki = kip1: psi1 = psi2: psi2 = psi3
    NEXT i
    u2 = psi3
    r2 = r

```

'routine to integrate the Schroedinger equation using the Numerov method
'for the modified Coulomb potential

```

    psi1 = 0: psi2 = (l% + 1) * 10 * dr ^ (l% + 1)
    r = dr
    'v = EXP(-3.7807 * z1 * r) * (1 + 1.8904 * z1 * r) + z
    v = (4 * (1 - 1 / (1.15287 * (EXP(4.9017 * r) - 1) + 1))) - z1)
    v = v * 14.3998 / r
    v = v + ll / (r * r)
    kim1 = cons * (e - v)
    r = 2 * dr
    'v = EXP(-3.7807 * z1 * r) * (1 + 1.8904 * z1 * r) + z
    v = (4 * (1 - 1 / (1.15287 * (EXP(4.9017 * r) - 1) + 1))) - z1)
    v = v * 14.3998 / r
    v = v + ll / (r * r)
    ki = cons * (e - v)
    FOR i = 2 TO nr - 1
        r = (i + 1) * dr
        'v = EXP(-3.7807 * z1 * r) * (1 + 1.8904 * z1 * r) + z
        v = (4 * (1 - 1 / (1.15287 * (EXP(4.9017 * r) - 1) + 1))) - z1)
        v = v * 14.3998 / r
        v = v + ll / (r * r)
        kip1 = cons * (e - v)
        ps = ((2 - 10 * ki) * psi2 - (1 + kim1) * psi1)
        psi3 = ps / (1 + kip1)
        kim1 = ki: ki = kip1: psi1 = psi2: psi2 = psi3
    NEXT i

```

```

ulb = psi3
FOR i = nr TO nr + 9999
  r = (i + 1) * dr
  'v = EXP(-3.7807 * z1 * r) * (1 + 1.8904 * z1 * r) + z
  v = (4 * (1 - 1 / (1.15287 * (EXP(4.9017 * r) - 1) + 1))) - z1)
  v = v * 14.3998 / r
  v = v + ll / (r * r)
  kip1 = cons * (e - v)
  ps = ((2 - 10 * ki) * psi2 - (1 + kim1) * psi1)
  psi3 = ps / (1 + kip1)
  kim1 = ki: ki = kip1: psi1 = psi2: psi2 = psi3
NEXT i
u2b = psi3

```

```

'routine to find the phase shift delta l
IF u1 < 0 THEN s1 = -1 ELSE s1 = 1
IF ulb < 0 THEN s2 = -1 ELSE s2 = 1
eta = -14.3998 * z / (hbarm * k)
dx = k * (r2 - r1) - eta * LOG(r2 / r1)
d1 = u2 - u1 * COS(dx)
IF d1 = 0 THEN
  x1 = s1 * pi / 2
ELSE
  x1 = ATN(u1 * SIN(dx) / d1)
END IF
d2 = u2b - ulb * COS(dx)
IF d2 = 0 THEN
  x2 = s2 * pi / 2
ELSE
  x2 = ATN(ulb * SIN(dx) / d2)
END IF
IF x1 < 0 THEN x1 = x1 + pi
IF s1 < 0 THEN x1 = x1 + pi
IF x2 < 0 THEN x2 = x2 + pi
IF s2 < 0 THEN x2 = x2 + pi
x3 = x2 - x1
IF x3 < 0 THEN x3 = x3 + 2 * pi
PRINT e, l%, x3
OPEN "data8" FOR APPEND AS #1
PRINT #1, e, l%, x3
CLOSE #1
NEXT l%
NEXT e

```

APPENDIX B

CROSS.BAS

```
'This program calculates the elastic scattering cross sections for
'electrons incident on a modified Coulomb potential from the
'Coulomb phases and the phase shifts delta l
DIM delta(20, 19), eta(20, 19), pl(20, 36), sigma(20, 36), sigmac(20, 36)
CLS
pi = 3.14159: hbarm = 7.62003:
'generate the Legendre polynomials using recursion relations
FOR i% = 0 TO 36      'this theta is such that it will only go from
    theta = i% * pi / 36 '0 to 180 degrees.
    x = COS(theta)
    pl(0, i%) = 1
    pl(1, i%) = x
    FOR l% = 1 TO 19
        pli = (2 * l% + 1) * x * pl(l%, i%)
        pl(l% + 1, i%) = (pli - l% * pl(l% - 1, i%)) / (l% + 1)
    NEXT l%
NEXT i%
'input the Coulomb phases eta and the phase shifts delta
OPEN "a:\phase2.txt" FOR INPUT AS #1
OPEN "a:\phase2c.txt" FOR INPUT AS #2
FOR i = 0 TO 20      'i is the angular momentum script
    FOR j = 0 TO 19  'j is the energy script
        INPUT #1, delta(i, j)
        INPUT #2, eta(i, j)
    NEXT j
NEXT i
CLOSE
'calculate the scattering cross sections for the Coulomb and modified
'Coulomb potential
FOR j = 0 TO 19      'j here is the energy script
    e = (j + 1) * 25 'these energies go from 25 to 500 eV in steps of 25eV
    k2 = 2 * e / hbarm: k = SQR(k2)
    n = -14.3998 * 2 / (hbarm * k)
    FOR th = 1 TO 36
        theta = th * pi / 36
        sin2 = (SIN(theta / 2)) ^ 2
        arg1 = 2 * eta(0, j) - n * LOG(sin2)
```

```

f1 = -n / (2 * k * sin2)
sigmac(j, th) = f1 * f1
freal = f1 * COS(arg1)
fimag = f1 * SIN(arg1)
FOR i = 0 TO 20 'i here is angular momentum l and it goes from 0 to 20
    sind = SIN(delta(i, j))
    f1 = (2 * l + 1) * sind * pl(i, th) / k
    arg1 = 2 * eta(i, j) + delta(i, j)
    freal = freal + f1 * COS(arg1)
    fimag = fimag + f1 * SIN(arg1)
NEXT i
sigma(j, th) = freal * freal + fimag * fimag
NEXT th
NEXT j
OPEN "a:\sigma.txt" FOR OUTPUT AS #1
FOR th = 1 TO 36
FOR j = 0 TO 19
PRINT #1, sigma(j, th);
NEXT j
PRINT #1,
NEXT th
CLOSE
OPEN "a:\sigma2c.txt" FOR OUTPUT AS #1
FOR th = 1 TO 36
FOR j = 0 TO 19
PRINT #1, sigmac(j, th);
NEXT j
PRINT #1,
NEXT th
CLOSE

```

APPENDIX C

OSAH2ANG.BAS

'This program calculates the cross section for the scattering in the forward
'direction of a 1s electron of H2 in a collision with an C2+ ion.

'(1e-18*cm^2/(eV*sr)). It uses the OSA2 from Wang et. al. (1991)

DIM sigma(20, 36), sig(600)

CLS

'input the differential scattering cross section for free electrons

'incident on C2+ in Angstrom^2/sr and convert it to au^2/sr

OPEN "c:\sigma.txt" FOR INPUT AS #1

FOR j = 1 TO 36

FOR i = 1 TO 20

INPUT #1, sigma(i, j)

sigma(i, j) = sigma(i, j) / .28

NEXT i

NEXT j

CLOSE

OPEN "c:\csxn1.log" FOR OUTPUT AS #1

'beam velocity is v

v = 4.49

'binding energy of the 1s electron is ei

ei = -15.422 / 27.21

'pick the energy of the scattered electron (el) in the lab frame

FOR angle = 32 TO 50 STEP 1

angle1 = angle * 3.14159 / 180

FOR el1 = 600 TO 1400 STEP 25

el = el1

'kl is the velocity in the lab frame (au)

kl = SQR(2 * el / 27.21)

'thet is the scattering angle in the projectile frame

thet = ATN(SIN(angle1) / (v / kl - COS(angle1)))

IF angle = 0 THEN thet = 3.14159

'kf is the velocity in the projectile frame

kf = kl * SIN(angle1) / (SIN(3.1416 - thet))

IF angle = 0 THEN kf = kl - v

'ef is the energy in the projectile frame (au)

ef = kf * kf / 2

'OSA2

FOR i = 0 TO 600

sig(i) = 0

NEXT i

qs2 = ef - ei

q = SQR(2 * qs2)

FOR i = 0 TO 600

thi = i / 650

qp = q * SIN(thi)

ql = q * COS(thi)

FOR j = 0 TO 400

phi = j * .0157079

arg = (ql - kf * COS(thet)) ^ 2 + (qp * COS(phi) - kf * SIN(thet)) ^ 2 + (qp * SIN(phi)) ^ 2

costh = 1 - .25 * arg / qs2

IF ABS(costh) < .001 THEN

theta = 90

ELSE

tanh2 = 1 / costh ^ 2 - 1

theta = 180 - ATN(SQR(tanh2)) * 57.2957795#

END IF

e1 = 27.21 * qs2

ee = INT(e1 / 25)

de = e1 - 25 * ee

th = INT(theta / 5)

dth = theta - 5 * th

IF ee > 19 THEN

sigi = sigma(20, th) + (sigma(20, th + 1) - sigma(20, th)) * dth / 5

ELSE

sigi = sigma(ee, th) + (sigma(ee + 1, th) - sigma(ee, th)) * de / 25

sigi = sigi + (sigma(ee, th + 1) - sigma(ee, th)) * dth / 5

END IF

sig(i) = sig(i) + sigi / 400

NEXT j

qm = SQR((ql - v) ^ 2 + qp ^ 2)

pqm = .97628 / (1 + 1.0211 * qm * qm) ^ 4

pqm = pqm + .28287 / (1 + .41271 * qm * qm) ^ 5

sig(i) = sig(i) * pqm * SIN(thi)

```

NEXT i
fac = 2
sum = 0
FOR i = 1 TO 599
  IF fac = 2 THEN fac = 4 ELSE fac = 2
  sum = sum + fac * sig(i)
NEXT i
sum = sum + sig(0) + sig(600).
sum = .0033136 * sum * kf
'sum is the differential cross section ( $1e-18 \text{ cm}^2 / (\text{eV} \cdot \text{sr})$ ) in
'the projectile frame
sum = sum * kl / kf
'sum is now the differential cross section in the laboratory frame
PRINT angle, el, sum * el * 1E-18
PRINT #1, angle, el, sum * el * 1E-18
NEXT el
NEXT angle

CLOSE

```

APPENDIX D

SIMULATE.EXE

Option Explicit

Dim Ay As Double

Dim ctr As Long

Dim d, V, s, Zlower, Zupper

Dim XiPos%(5000), YiPos%(5000), ZiPos%(5000)

Dim Vxi%(5000), Vyi%(5000), Vzi%(5000)

Dim XfPos%(5000), ZfPos%(5000)

Dim u, recnum, qo, q As Long

Dim a, B, C, Ao, Bo, Co, radius

Dim Vx, Vy, Vz, t, A1, B1, A2, B2

Dim Xo, Yo, Zo, Vxo, Vyo, Vzo

Dim t1, X1, Y1, Z1, Vx1, Vy1, Vz1

Dim t2, Y2max, X2, Y2, Z2

Dim Vx2, Vy2, Vz2

Dim X3, Y3, Z3, Vx3, Vy3, Vz3, t3

Dim X4, Y4, Z4, t4, Ay4, Vbias

Dim X5, Y5, Z5, L, G

Dim i

Dim Vxmax%, Vxmin%, Vymax%, Vymin%, Vzmax%, Vzmin%

Dim ezmax, ezmin, exvalue, eymax, eymin, absvolt As Single

Dim time1, time2 As Single

Dim loopcounter, events As Double

Dim testvelocity As Double

Sub cmdExit_Click ()

End

End Sub

Sub cmdStart_Click ()

picGraph.Scale (-3795, 16190)-(3795, 6920)

picGraph.Line (-3795, 16190)-(3795, 6920), RGB(255, 0, 0), B

Call one

End Sub

```

Sub graphthem ()
For L = 1 To 5000
picGraph.PSet (XfPos%(L), ZfPos%(L))
Next L
qo = q
recnum = 1

End Sub

Sub one ()

events = txtSuccess.Text 'This is the number of successful
                        'events that will take place and
                        'be saved. This is also what you
                        'you input from the form.

time1 = Timer           'This just takes the initial time
                        'in order to keep tract of how
                        'long it took to execute the program.

Vbias = txtVbias.Text 'input the bias voltage from the form

V = txtVoltage.Text'input the analyzer voltage from the form
'Note that the analyzer voltage is negative.

'd = 36.1 'in mm 'This the seperation between the earth
            'plate and the plate that you put the
            'negative voltage on.

d = 36.65
'd = 37.1

s = .00876 'in meters 'This is the seperation between the
            'focal plane and the front of the
            'channel plate.

Ay = -175630000000000# * (V / d)' in meters/second squared
Ay4 = (1.6E-19 / 9.11E-31) * (Vbias / s)'here I am defining the
'the accleration due to the bias voltage.

Zlower = 69.2 'in mm
Zupper = 161.9 'in mm
u = 0'this counter is to monitor how many successfull events
recnum = 1 'this counter is for saving the data after

```

'every 5000 events
qo = 1 'this is the initial position of the binary file.

Randomize Timer
Vxmax% = -30000
Vxmin% = 30000
Vymax% = -30000
Vymin% = 30000
Vzmax% = -30000
Vzmin% = 30000

'Here is where I am going to define all the values that i
'need for automatic translation of velocities depending on
'the analyzer voltage.

'ezmax, ezmin etc are some constants that are related to
'the velocities in the following way:
'ezmax = ((vzmax)^2)/|analyzer voltage|

"ezmax = 1115000000000# 'this is the value before 3/14/96
"ezmin = 7656000000000#
ezmax = 10989000000000# 'this the value as of 3/14/96; it has
ezmin = 7598950000000# 'changed because the distance between
 'the earth plate and the analyzing
 'plate has changed slightly which resulted
 'in a little different fit of energy vs. channel
 'number fit which then translated in to a little
 'different analyzer constant.

exvalue = 176600000000#
eymax = 244120000000#
eymin = 61029900000#
absvolt = Abs(V)

txtDone.Text = "I am working so please don't bother me!"

Do

 DoEvents

 Call test1

 If radius < .5 Then GoTo 10 Else GoTo 90

 10 ctr = ctr + 1 'this just keeps tract of how many events

'will be counted as good events.

Call test2

Call test3

If A1 > -1.5 And A1 < 1.5 And B1 > -1 And B1 < 1 Then GoTo 22 Else GoTo 90
22

DoEvents

Call test4

If A2 > -11.5 And A2 < 11.5 And B2 > -3 And B2 < 3 Then GoTo 24 Else GoTo
90
24

Call test5

'now do the test to find out if thhe electron makes it within the
'slot of the earth plane.

If Z1 > -6.5 And Z1 < 6.5 And X1 > -19 And X1 < 19 Then GoTo 25 Else GoTo 90

25

DoEvents

Call test6

If Y2max > d Then GoTo 90 Else GoTo 26
26

Call test7

'now see if the electron is within the analyzer or not.

If Z2 > 108.3 And Z2 < 214 And X2 > -37.95 And X2 < 37.95 Then GoTo 27 Else
GoTo 90

27 Call test8

'now check if X4 and Z4 are within the focal plane limits.

If X4 > -37.95 And X4 < 37.95 And Z4 > 39.2 And Z4 < 161.9 Then GoTo 29 Else
GoTo 90

29 DoEvents

Call test9

'now see if the electrons are within the limits of the chanel-plate.

If Z5 > Zlower And Z5 < Zupper And X5 > -37.95 And X5 < 37.95 Then GoTo 30
Else GoTo 90

30

XiPos%(recnum) = Ao * 1000

```

YiPos%(recnum) = Bo * 1000
ZiPos%(recnum) = Co * 1000
Vxi%(recnum) = Vx / 10000
Vyi%(recnum) = Vy / 10000
Vzi%(recnum) = Vz / 10000
XfPos%(recnum) = 100 * X5
ZfPos%(recnum) = 100 * Z5

```

```

recnum = recnum + 1 'I'm incrementing the recnum counter.
u = u + 1'number of successful events

```

```

If recnum = 5001 GoTo 85 Else GoTo 90
85

```

```

    Call savethem
    DoEvents

```

```

    Call graphthem
    time2 = Timer
    txtTimer.Text = (time2 - time1)'the time it took to do this much.

```

```

90 'txtDisplay5.Text = u
Loop Until u = events
txtDone.Text = "I am done!"

```

```

End Sub

```

```

Sub savethem ()
q = q0
Open txtOutputfile.Text For Binary As #1
For L = 1 To 5000
Put #1, q, XiPos%(L)
    q = q + 2
Put #1, q, YiPos%(L)
    q = q + 2
Put #1, q, ZiPos%(L)
    q = q + 2
Put #1, q, Vxi%(L)
    q = q + 2
Put #1, q, Vyi%(L)
    q = q + 2
Put #1, q, Vzi%(L)
    q = q + 2
Put #1, q, XfPos%(L)

```

```

        q = q + 2
Put #1, q, ZfPos%(L)
        q = q + 2
Next L
Close #1
txtDisplay5.Text = u
txtDisplay4.Text = ctr
For L = 1 To 5000
If Vxi%(L) > Vxmax% Then Vxmax% = Vxi%(L)
If Vxi%(L) < Vxmin% Then Vxmin% = Vxi%(L)

If Vyi%(L) > Vymax% Then Vymax% = Vyi%(L)
If Vyi%(L) < Vymin% Then Vymin% = Vyi%(L)

If Vzi%(L) > Vzmax% Then Vzmax% = Vzi%(L)
If Vzi%(L) < Vzmin% Then Vzmin% = Vzi%(L)

Next L

```

```

txtVxmin.Text = Vxmin%
txtVxmax.Text = Vxmax%

```

```

txtVymin.Text = Vymin%
txtVymax.Text = Vymax%

```

```

txtVzmin.Text = Vzmin%
txtVzmax.Text = Vzmax%

```

```

Vxmax% = -30000
Vxmin% = 30000
Vymax% = -30000
Vymin% = 30000
Vzmax% = -30000
Vzmin% = 30000

```

```

End Sub

```

```

Sub test1 ()
a = Rnd
B = Rnd
C = Rnd
Ao = a - .5 'x position in mm
Bo = B - .5 'y position in mm

```

Co = 10 * C - 5 'z position in mm
radius = Sqr(Ao * Ao + Bo * Bo)'radius of the beam

End Sub

Sub test2 ()

backtome:

'Z component of velocity in meters/second

Vz = (Sqr(ezmax) - (Sqr(ezmax) - Sqr(ezmin)) * Rnd(1)) * Sqr(absvolt)

"Vz = 9815000# * (1 - .1 * Rnd(1)) 'This is the velocity I

'found for analyzer voltage

'equals to -97.7 volts. This is

'when the peak will fall approximately

'in the middle of the channel plate.

Vx = Rnd(1)

'X component of velocity in meters/second

Vx = (2 * Vx - 1) * Sqr(exvalue * absvolt)

"testvelocity = Sqr(Vx ^ 2 + Vz ^ 2)

"If testvelocity >= 9715000# And testvelocity <= 9815000# Then GoTo yomama:

Else GoTo backtome:

yomama:

Vy = .91 * Rnd(1)

'Y component of velocity in meters/second

Vy = (Sqr(eymax) * Vy - Sqr(eymin)) * Sqr(absvolt)

End Sub

Sub test3 ()

'now see if the electron makes it out of the gas-cell or not.

t = (6.5 - Co) / (1000 * Vz)'in seconds

A1 = Ao / 1000 + Vx * t'in meters

B1 = Bo / 1000 + Vy * t'in meters

A1 = A1 * 1000 'in mm

B1 = B1 * 1000 'in mm

End Sub

Sub test4 ()

t = (30.5 - Co) / (1000 * Vz)

A2 = Ao / 1000 + Vx * t 'in meters

B2 = Bo / 1000 + Vy * t 'in meters

$A2 = A2 * 1000$ 'in mm
 $B2 = B2 * 1000$ 'in mm

End Sub

Sub test5 ()

'now find the positions in the earth frame (Xo,Yo,Zo) etc.

'so first find (Ao,Bo,Co) ---> (Xo,Yo,Zo).

$Xo = Ao$ 'initial x-position in mm.

$Yo = -(Co - 58) * .5 + Bo * .866$ 'initial y-position in mm.

$Zo = (Co - 58) * .866 + Bo * .5$ 'initial z-position in mm.

'now find the velocities in the earth frame (Vxo,Vyo,Vzo)

'so first convert (Vx,Vy,Vz) ---> (Vxo,Vyo,Vzo)

$Vxo = Vx$ 'velocity in earth frame in meters/sec

$Vyo = Vy * .866 - Vz * .5$ 'velocity in earth frame in meters/sec

$Vzo = Vy * .5 + Vz * .866$ 'velocity in earth frame inn meters/sec

'now find out when $Y1=0$ and find $X1$ and $Z1$ positions at that time.

$t1 = -Yo / (1000 * Vyo)$ 'time it takes an electron to make it to $Y1=0$.

$X1 = Xo / 1000 + Vxo * t1$ 'position in meters

$Z1 = Zo / 1000 + Vzo * t1$ 'position in meters

$X1 = X1 * 1000$ 'position in mm

$Z1 = Z1 * 1000$ 'position in mm

End Sub

Sub test6 ()

'velocities at (X1,Y1,Z1) are the same as they were at (Xo,Yo,Zo)

'so let's define them again.

$Vx1 = Vxo$

$Vy1 = Vyo$

$Vz1 = Vzo$

'now find out at what time will the electron reach the other side

'of the plate, that is to say when will $Y2$ be zero $Y2 = 0$.

$t2 = -2 * Vy1 / Ay$ 'time it takes to reach the otherside of the plate.

'now find the maximum height in y-direction.

$Y2max = -(Vy1 * Vy1) / (2 * Ay)$ 'maximum height in meters.

$Y2max = -Y2max * 1000$ 'height in mm.

End Sub

Sub test7 ()

'now find the positions of X2 and Z2.

$X2 = X1 / 1000 - 2 * Vx1 * Vy1 / Ay$ 'position in meters

$Z2 = Z1 / 1000 - 2 * Vz1 * Vy1 / Ay$ 'position in meters

$X2 = X2 * 1000$ 'position in mm

$Z2 = Z2 * 1000$ 'position in mm

'now transform the velocities in meters/second

$Vx2 = Vx1$ 'in meters/second

$Vy2 = -Vy1$ 'in meters/second

$Vz2 = Vz1$ 'in meters/second

End Sub

Sub test8 ()

'now transform (X2,Y2=0,Z2) to a new tilted coordinate system.

'(X2,Y2=0,Z2) ----> (X3,Y3,Z3).

$X3 = X2$ 'position in mm

$Y3 = -(Z2 - 108.3) * .1891$ 'position in mm

$Z3 = (Z2 - 108.3) * .982$ 'position in mm

'now transform the velocities in meters/second

$Vx3 = Vx2$

$Vy3 = -Vz2 * .1891 + Vy2 * .982$ 'meters/second

$Vz3 = Vz2 * .982 + Vy2 * .1891$ 'meters/second

'now find out at what time Y4=0 and then at that time find out

'what X4 and Z4 are.

$t3 = -Y3 / (1000 * Vy3)$ 'time to make Y4 = 0

$X4 = X3 / 1000 + Vx3 * t3$ 'position in meters

$Z4 = Z3 / 1000 + Vz3 * t3$ 'position in meters

$X4 = X4 * 1000$ 'position in mm

$Z4 = Z4 * 1000$ 'position in mm

End Sub

Sub test9 ()

'now check if the electrons make it to the chanel plate.

'But first check to see if the bias voltage was non-zero.

'Depending on the value of the bias voltage it will take

'different amount of time for the electron to travell to

'the chanel plate from the focal plane.

If Vbias = 0 Then GoTo here Else GoTo there
there:

If $Vy3^2 > -(2 * s * Ay4)$ Then GoTo comehere Else GoTo gothere
comehere:

$t4 = (-Vy3 + \text{Sqr}(Vy3^2 + 2 * s * Ay4)) / Ay4$

GoTo comeonover:

gothere: 'if it fails the test of positive root it will come here
'in that case I have to set the values of X5 and Z5 to be zero so that
'they fail the test of reaching the anode.

X5 = 0

Z5 = 0

'now go to the end of the subroutine.

GoTo comeonhere:

here: 'if there is no bias voltage set then this line should be
'executed first.

$t4 = s / Vy3$ 'time it takes to reach the chanel plate.

comeonover: 'here is where you come after you have computed
'the valid time t4.

$X5 = X4 / 1000 + Vx3 * t4$ 'in meters

$Z5 = Z4 / 1000 + Vz3 * t4$ 'in meters

$X5 = X5 * 1000$ 'in mm

$Z5 = Z5 * 1000$ 'in mm

comeonhere:

End Sub

APPENDIX E

SORT.EXE

'This program is to sort data from a data file called
'trial.bin. trial.bin is a binary file which is 64 mega-
'bytes long. And the data from that file will be sorted
'in chunks of 20,000 events at a time.

Dim Vxmin(64, 64), Vxmax(64, 64), Vxavg(64, 64) As Single
Dim Velx(64, 64) As Single
Dim Vymin(64, 64), Vymax(64, 64), Vyavg(64, 64) As Single
Dim Vely(64, 64) As Single
Dim Vzmin(64, 64), Vzmax(64, 64), Vzavg(64, 64) As Single
Dim Velz(64, 64) As Single
Dim Emin(64, 64), Emax(64, 64), Eavg(64, 64) As Single
Dim Energy(64, 64) As Single
Dim E(20000) As Single
Dim xz(64, 64) As Long
Dim Velocity(64, 64) As Single

Dim Xi%(20000), Yi%(20000), Zi%(20000)
Dim Vx%(20000), Vy%(20000), Vz%(20000)
Dim Xfinal%(20000), Zfinal%(20000)
Dim q, p As Long

Dim loopcounter As Single

Dim angle(64, 64) As Single

Sub cmdExit_Click ()
Close

End

End Sub

Sub cmdStart_Click ()
Call fireup

End Sub

```

Sub fireup ()
loopcounter = txtLoop.Text
q = 1 'initial position in the trial.bin file.
p = 1
Open txtFilename.Text For Binary As #1

Call setvalues
txtDone.Text = "I'm working please leave me alone."
Do

DoEvents
Call gather

DoEvents
Call sort
counter = counter + 1
txtDisplay.Text = counter * 20000

DoEvents
Loop Until counter = loopcounter

Close #1

Call store
txtDone.Text = "I am done."
End Sub

Sub gather ()
For i = 1 To 20000
DoEvents
Get #1, q, Xi%(i)
    q = q + 2
Get #1, q, Yi%(i)
    q = q + 2
Get #1, q, Zi%(i)
    q = q + 2
Get #1, q, Vx%(i)
    q = q + 2
Get #1, q, Vy%(i)
    q = q + 2
Get #1, q, Vz%(i)
    q = q + 2
Get #1, q, Xfinal%(i)

```

```

        q = q + 2
    Get #1, q, Zfinal%(i)
        q = q + 2
    DoEvents
Next i
txtDisplayq.Text = q
For j = 1 To 20000
    DoEvents
    If Zfinal%(j) < 6920 Or Zfinal%(j) > 16190 Then txtDisplayz.Text = Zfinal%(j)
    If Xfinal%(j) < -3795 Or Xfinal%(j) > 3795 Then txtDisplayx.Text = Xfinal%(j)
    DoEvents
Next j

```

End Sub

Sub setvalues ()

'initially set the min and the max values to some ridiculous-
'lously high and low values so that it is easy to compare
'during the sorting process.

```

For i = 1 To 64
    For j = 1 To 64
        Vxmin(i, j) = 1E+30
    Next j
Next i

```

```

For i = 1 To 64
    For j = 1 To 64
        Vxmax(i, j) = -1E+30
    Next j
Next i

```

```

For i = 1 To 64
    For j = 1 To 64
        Vymin(i, j) = 1E+30
    Next j
Next i

```

```

For i = 1 To 64
    For j = 1 To 64
        Vymax(i, j) = -1E+30
    Next j
Next i

```

```

For i = 1 To 64
For j = 1 To 64
Vzmin(i, j) = 1E+30
Next j
Next i

```

```

For i = 1 To 64
For j = 1 To 64
Vzmax(i, j) = -1E+30
Next j
Next i

```

```

For i = 1 To 64
For j = 1 To 64
Emin(i, j) = 1E+30
Next j
Next i

```

```

For i = 1 To 64
For j = 1 To 64
Emax(i, j) = -1E+30
Next j
Next i

```

End Sub

```

Sub sort ()
For i = 1 To 20000
DoEvents
If Xfinal%(i) > 3795 Or Xfinal%(i) < -3795 Then GoTo bla:
If Zfinal%(i) > 16190 Or Zfinal%(i) < 6920 Then GoTo bla:

```

```

Xfinal%(i) = (7590 + (Xfinal%(i) - 3795))

```

'here is where I am binning according to to what the final
'position is.

```

x = CInt(Xfinal%(i) / 118.59)

```

```

z = CInt((Zfinal%(i) - 6920) / 144.84)

```

'I just want to discard if any of the x or z bins turns out
'tobe out of range.

```

If x > 64 Or x < 1 Then GoTo bla:

```

```

If z > 64 Or z < 1 Then GoTo bla:

```

'now compare the min-max values

If $Vx\%(i) < Vxmin(x, z)$ Then $Vxmin(x, z) = Vx\%(i)$

If $Vx\%(i) > Vxmax(x, z)$ Then $Vxmax(x, z) = Vx\%(i)$

If $Vy\%(i) < Vymin(x, z)$ Then $Vymin(x, z) = Vy\%(i)$

If $Vy\%(i) > Vymax(x, z)$ Then $Vymax(x, z) = Vy\%(i)$

If $Vz\%(i) < Vzmin(x, z)$ Then $Vzmin(x, z) = Vz\%(i)$

If $Vz\%(i) > Vzmax(x, z)$ Then $Vzmax(x, z) = Vz\%(i)$

'now compute the energy value and compare with the emin-emax

'compute the energy in terms of eV.

$E(i) = (.00028469) * (Vx\%(i) ^ 2 + Vy\%(i) ^ 2 + Vz\%(i) ^ 2)$

'now compare with Emin and Emax

If $E(i) < Emin(x, z)$ Then $Emin(x, z) = E(i)$

If $E(i) > Emax(x, z)$ Then $Emax(x, z) = E(i)$

'now increment the bin value of the particular bin by one.

$xz(x, z) = xz(x, z) + 1$

$Velx(x, z) = Velx(x, z) + Vx\%(i)$

$Vely(x, z) = Vely(x, z) + Vy\%(i)$

$Velz(x, z) = Velz(x, z) + Vz\%(i)$

$Energy(x, z) = Energy(x, z) + E(i)$

bla:

DoEvents

Next i

End Sub

Sub store ()

Open txtOutputfile.Text + "vxavg.dat" For Output As #2

Open txtOutputfile.Text + "vyavg.dat" For Output As #3

Open txtOutputfile.Text + "vzavg.dat" For Output As #4

Open txtOutputfile.Text + "emin.dat" For Output As #5

Open txtOutputfile.Text + "emax.dat" For Output As #6

Open txtOutputfile.Text + "eavg.dat" For Output As #7

Open txtOutputfile.Text + "velocity.bin" For Binary As #8

Open txtOutputfile.Text + "2dpos.bin" For Binary As #9

Open txtOutputfile.Text + "angle.col" For Output As #10

'First find what the Vxavg is and then save it.

```
For i = 1 To 64
For j = 1 To 64
If xz(i, j) = 0 Then xz(i, j) = 1
Vxavg(i, j) = Velx(i, j) / xz(i, j)
Next j
Next i
```

```
For ctrl = 1 To 64
For ctr2 = 1 To 64
Print #2, Vxavg(ctrl, ctr2), ",",
Next ctr2
Print #2,
Next ctrl
Close #2
```

'First find what the Vyavg is and then save it.

```
For i = 1 To 64
For j = 1 To 64
If xz(i, j) = 0 Then xz(i, j) = 1
Vyavg(i, j) = Vely(i, j) / xz(i, j)
Next j
Next i
```

```
For ctrl = 1 To 64
For ctr2 = 1 To 64
Print #3, Vyavg(ctrl, ctr2), ",",
Next ctr2
Print #3,
Next ctrl
Close #3
```

'First find what the Vzavg is and then save it.

```
For i = 1 To 64
For j = 1 To 64
If xz(i, j) = 0 Then xz(i, j) = 1
Vzavg(i, j) = Velz(i, j) / xz(i, j)
Next j
Next i
```

```
For ctrl = 1 To 64
For ctr2 = 1 To 64
Print #4, Vzavg(ctrl, ctr2), ",",
```

```
Next ctr2
Print #4,
Next ctr1
Close #4
```

```
'Save Emin
For ctr1 = 1 To 64
For ctr2 = 1 To 64
Print #5, Emin(ctr1, ctr2), ",",
Next ctr2
Print #5,
Next ctr1
Close #5
```

```
'Save Emax
For ctr1 = 1 To 64
For ctr2 = 1 To 64
Print #6, Emax(ctr1, ctr2), ",",
Next ctr2
Print #6,
Next ctr1
Close #6
```

```
'First find what the Eavg is and then save it.
For i = 1 To 64
For j = 1 To 64
If xz(i, j) = 0 Then xz(i, j) = 1
Eavg(i, j) = Energy(i, j) / xz(i, j)
Next j
Next i
```

```
For ctr1 = 1 To 64
For ctr2 = 1 To 64
Print #7, Eavg(ctr1, ctr2), ",",
Next ctr2
Print #7,
Next ctr1
Close #7
```

```
'now find the velocities.
For i = 1 To 64
For j = 1 To 64
Velocity(i, j) = Sqr((Vxavg(i, j)) ^ 2 + (Vyavg(i, j)) ^ 2 + (Vzavg(i, j)) ^ 2)
```

```

Next j
Next i
'now save the velocities.
p = 1 'set the pointer to 1
For i = 1 To 64
For j = 1 To 64
Put #8, p, Velocity(i, j)
p = p + 4
Next j
Next i
Close #8

'now save how many events fall within each bin.
p = 1 'set the pointer to 1
For i = 1 To 64
For j = 1 To 64
Put #9, p, xz(i, j)
p = p + 4
Next j
Next i
Close #9

'first find the inverse tangent of the angle
For i = 1 To 64
For j = 1 To 64
angle(i, j) = Atn(Vxavg(i, j) / Vzavg(i, j))
Next j
Next i

'now save the angles
For i = 1 To 64
For j = 1 To 64
Print #10, i, j, angle(i, j)
Next j
Next i
Close #10

End Sub

```

APPENDIX F

EXTCSXN.EXE

```
Sub cmdExit_Click ()  
End
```

End Sub

```
Sub cmdPreviousForm_Click ()  
form3.Hide  
form2.Show
```

End Sub

```
Sub cmdStart_Click ()  
Call start  
End Sub
```

```
Sub define ()  
'Here is where I am going to define all the values that i  
'need for automatic translation of velocities depending on  
'the analyzer voltage.
```

```
'ezmax, ezmin etc are some constants that are related to  
'the velocities in the following way:
```

```
'ezmax = ((vzmax)^2)/analyzer voltage|
```

```
"ezmax = 1115000000000#
```

```
"ezmin = 765600000000#
```

```
ezmax = 1098900000000# 'new values for these constants
```

```
ezmin = 759895000000#
```

```
exvalue = 17660000000#
```

```
eymax = 24412000000#
```

```
eymin = 6102990000#
```

```
absvolt = Abs(volts)
```

End Sub

```
Sub maxmin ()
```

```
'Find max and min velocities to determin Velocity space.
```

```

'Z component of velocity in meters/second
Vzmax = (Sqr(ezmax)) * Sqr(absvolt)
Vzmin = (Sqr(ezmax) - (Sqr(ezmax) - Sqr(ezmin))) * Sqr(absvolt)
'X component of velocity in meters/second
Vxmax = Sqr(exvalue) * Sqr(absvolt)
Vxmin = -Sqr(exvalue) * Sqr(absvolt)

'Y component of velocity in meters/second
Vymax = (Sqr(eymax) * .91 - Sqr(eymin)) * Sqr(absvolt)
Vymin = -Sqr(eymin) * Sqr(absvolt)

'now that I have all the max and min values I can find
'the velocity phase space volume.
Vspace = (Vxmax - Vxmin) * (Vymax - Vymin) * (Vzmax - Vzmin)
txtVspace.Text = Vspace'the value for the velocity space is
                'printed out in its appropriate box.

```

End Sub

Sub modify ()

'first define a multiplicative constant

'I am multiplying with the number of tries because all the
'in the transmission file need to be divided by the total
'number of tries in the simulation.

'I am multiplying by 10000 because I had to divide all the
'velocity entries in the data.bin file by 10000 in order
'for them to be smaller than 32000; so now I am
'compensating for it.

```

con = (tries * 10000 * 10000 * 10000) * deadtime / ((2 * Np * Vspace * n * (eff /
100) * press * l) * (recoil / 100))
txtResults.Text = con
For i = 1 To 640
For j = 1 To 640
Next j
Next i
txtResults.Text = "computing cross section"

```

'now multiply and divide appropriately the three files
'now i find (Double differential cross-section)*(Energy)
For i = 1 To 64

```

For j = 1 To 64
csec(i, j) = con * img(i, j) * (V(i, j) ^ 3) / xz(i, j)
Next j
Next i

End Sub

Sub openem ()

Open a$ For Binary As #1

pointer = 1 'initial starting position in the image file

'now gather the values from file #1
txtResults.Text = "Image file"
For i = 1 To 640
For j = 1 To 640
Next j
Next i

For i = 1 To 64
For j = 1 To 64
Get #1, pointer, bla
img(i, j) = bla
'txtResults.Text = img(i, j)

pointer = pointer + 4
Next j
Next i
Close #1

Open b$ For Binary As #2

pointer = 1 'initial position in the velocity file.
txtResults.Text = "Velocities"
For i = 1 To 640
For j = 1 To 640
Next j
Next i

For i = 1 To 64
For j = 1 To 64
Get #2, pointer, bla

```

V(i, j) = bla

'txtResults.Text = V(i, j)

pointer = pointer + 4

Next j

Next i

Close #2

Open c\$ For Binary As #3

pointer = 1'initial position in the transmission file.

txtResults.Text = "Positions"

For i = 1 To 640

For j = 1 To 640

Next j

Next i

For i = 1 To 64

For j = 1 To 64

Get #3, pointer, bla

xz(i, j) = bla

'txtResults.Text = xz(i, j)

pointer = pointer + 4

Next j

Next i

Close #3

End Sub

Sub saveem ()

'Open d\$ For Binary As #4

pointer = 1

'For i = 1 To 64

'For j = 1 To 64

'Put #4, pointer, csec(i, j)

'DoEvents

'txtResults.Text = csec(i, j)

```

'DoEvents
'pointer = pointer + 8
Next j
Next i
'Close #4
txtResults.Text = "Saving!"
'This saves it in the coloum format so that Sigma-Plot
'can plot the data.
Open d$ + ".dat" For Output As #5
For i = 1 To 64
For j = 1 To 64
energyaxis = ((j + 145.7) / 67.35) * absvolt
Print #5, i, energyaxis, csec(i, j)
Next j
Next i
Close #5

'This saves it in the matrix format
Open d$ + ".mat" For Output As #4
For i = 1 To 64
For j = 1 To 64
Print #4, csec(i, j), ",",
Next j
Print #4,
Next i
Close #4

End Sub

Sub start ()
form1.Hide
form2.Hide
form3.Show
DoEvents

'volts = txtVolts.Text 'analyzer voltage
'eff = txtEff.Text'chanel plate efficiency
'press = txtPressure.Text'pressure in the gas cell
'l = txtLength.Text'effective length of the gas cell
'n = txtNumber.Text'number of target atoms per cubic
    'centimeter per mTorr
'Np = txtProjectile.Text'number of projectile ions passing
    'through the gas-cell

```

```
'tries = txtTries.Text'number of total tries in the  
      'simulation program  
'deadtime = txtDeadtime.Text 'deadtime correction  
'recoil = txtRecoil.Text 'recoil ion detector efficiency  
'a$ = txtFile1.Text'name of the image file  
'b$ = txtFile2.Text'name of the velocity file  
'c$ = txtFile3.Text'name of the transmission file  
'd$ = txtFile4.Text'name of the file to save
```

```
Call define  
DoEvents  
Call maxmin  
DoEvents
```

```
Call openem  
DoEvents
```

```
Call modify  
DoEvents
```

```
Call saveem  
txtResults.Text = "I am done!"
```

```
End Sub
```

VITA

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During Dharmin's graduate career in Atomic Physics, he has received authorship on several journal articles and contributed papers:

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