Measurements of Differential Electron-Emission Cross Sections in Collisions of Fast Carbon Ions with Helium Atoms

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ABSTRACT

Cross sections doubly differential in angle and electron energy \((d^2\sigma/dE_d\Omega)\), for emission of electrons in collisions of 2.5 \(MeV/u\) \(C^{5+}\) and \(C^{4+}\) \((v_p = 10 \text{ au})\) ions with helium atoms are reported. Data were obtained at scattering angles ranging from 15° to 160° with respect to the projectile direction, and for electron energies from 1.0 \(eV\) to a maximum of 6.0 \(keV\). The detector resolution is 5.0% in energy and ±1.0° in angle. From these data, singly differential cross sections in energy \((d\sigma/dE_e)\) and angle \((d\sigma/d\Omega_e)\) were computed. Experimental results are compared with continuum-distorted-wave \((CDW)\) and first Born \((B1)\) theoretical calculations. For the case of \(C^{4+}\) projectiles, evidence for the presence of a small component of metastable 1s2s(\(^3S\)) ions in the beam is noted.

I. INTRODUCTION

Ionization is a prominent process in ion-atom collisions at moderate \((keV/u)\) to high \((MeV/u)\) impact energies. In addition to moderately high cross sections (probabilities) for ionization events, there is typically a very large energy loss per collision compared to charge transfer and excitation processes. Consequently, ionization processes are of considerable importance to a wide variety of investigators studying energy deposition in matter by fast projectiles. Examples of fields in which data on collisional ionization are needed include plasma fusion, auroral and other aeronomical investigations, astrophysics and studies of radiation effects in biological and other materials.

Considerable information on the dynamics of ionization has been gleaned from detailed studies of doubly differential cross sections \((DDCS)\), revealing the energy and angular distributions of the scattered electrons. The reaction of a singly charged projectile \(P^+\) with a neutral target \(T\) is generically expressed \(P^+ + T \rightarrow P^+ + T^+ + e^- (E_e,\theta)\) where \(E_e\) is the final kinetic energy of the liberated electron and \(\theta\) is its ejection angle with respect to the initial projectile direction.

Experimental studies of DDCS involving proton impact on numerous different target atoms and molecules over a wide range of collision energies are numerous [1-2]. To facilitate theoretical models relying on approximate wave functions describing the initial state of the collision system, Gealy et al [3-4] measured DDCS from medium-energy proton impact with atomic hydrogen (the only system for which exact wave functions are known). Hsu et al [5-6] measured DDCS for He\(^+\) impact on molecular and atomic hydrogen.

More recently, Tribedi et al have extend these measurements to include more highly charged projectiles, in particular 2.5 \(MeV/u\) \(C^{6+}\) impact on molecular [7] and atomic [8]...
hydrogen, and helium [9]. The present study is a continuation of this work to include 1- and 2-electron carbon ion projectiles on helium targets at the same impact velocity. In addition, we include extensive theoretical calculations carried out by Dr. Laszlo Gulyás of the Institute of Nuclear Research, Hungarian Academy of Science (ATOMKI), Debrecen, Hungary.

II. EXPERIMENT

A. Preparation of Projectiles

Negative carbon ions (C⁻) were prepared in a Middleton sputter ion source [10] and electrostatically accelerated to 40 keV for injection into the tandem Van de Graaff accelerator (Fig 1). A cylindrical terminal in the center of the accelerator was raised to a high positive voltage (HV = 7.5 million volts max). Upon injection, the C⁻ ions were accelerated toward the terminal where they passed through a gas cell, which stripped two or more electrons from many of the negative ions. The beam emerging from the cell contained a distribution of positive charge states, (C⁺, C²⁺, C³⁺ etc) each of which was subsequently repelled from the terminal, thus accelerating it again (hence the name “tandem”) along its direction of motion.

![Figure 1. Tandem Van de Graaff Accelerator](image)

The final kinetic energy of an ion of charge state \( n \) is \( E(MeV) = 0.04 + (1 + n) \cdot e \cdot HV \) where \( e \) is the electronic charge. The term 0.04MeV accounts for the injection energy. The various charge states exiting the tandem thus have differing kinetic energies. We determined the value of \( HV \) by solving this equation for the desired energy and charge state: \( HV = \frac{(E - 0.04)MeV}{1 + n} \). For \( \frac{1}{2} C^{5+} \) at 2.5MeV/u, we needed a total energy of 30MeV. Thus, the terminal voltage used for \( C^{5+} \) was about 5.0MV and that for \( C^{4+} \) was about 6.0MV.
After the beam emerged from the accelerator, it passed through a series of electric and magnetic devices that filtered the beam for the desired charge state and focused and steered the beam to the desired target area. (It typically takes a skilled operator about half a day to get the appropriate beam focused into the target chamber.) For a sense of scale, the large outer cylinder shown in Fig. 1 is about 8 feet in diameter and forty feet long.

**B. Target Chamber**

The target region was in a vacuum chamber approximately 60cm in diameter. This chamber was nearly 50m downstream from the ion source. The background pressure was less than $10^{-7}$ Torr (about $10^{-10}$ atm). Helium gas from a high-pressure canister was admitted to the chamber through a mechanical leak valve downstream from a pressure regulator. During introduction of target gas, the aperture to the turbo-molecular pump was throttled and helium gas admitted to the chamber to a pressure of typically 0.1 – 0.3 mT, forming a static gas target with very nearly constant pressure. The throttling of the aperture was necessary to reduce the total gas load on the turbo pump. Target pressure was monitored and measured with a capacitance manometer.

The chamber was magnetically shielded to preserve the integrity of the trajectories of very low energy electrons (down to 1.0 eV). This shielding was provided by the combination of a mu-metal lining inside the chamber and a single Helmholtz coil outside the chamber. The current in the coil was adjusted until the absolute magnitude of the field did not exceed 10mG anywhere along the trajectories of the scattered electrons.

Scattered electrons were energy-analyzed by a hemispherical analyzer with inner and outer electrode radii of 2.5 cm and 3.5 cm, respectively. Its energy resolution was

$$ R = \frac{\Delta E_{\text{pass}}}{E_{\text{pass}}} = 5.0\% , $$

where $E_{\text{pass}}$ is the kinetic energy of the electrons inside the analyzer.

The analyzer was fronted by collimating apertures that defined an effective solid-angle-path-length

$$ \int \Omega(z)dz = 0.00126 \text{ cm sr} , $$

where $\theta$ is the scattering angle with respect to the projectile direction. There was also an accelerating/decelerating electrode for diagnostic procedures and adjustment of the effective energy resolution. Under normal operating conditions, this electrode was biased at $V_a = +5V$ for scattered electron energies below 12eV, and 0V for electron energies above 12eV. The acceleration of the very slow electrons improved the efficiency with which they were detected. This provided a pass energy $E_{\text{pass}} = E_e + eV_a$. 
At the exit of the analyzer, electrons were detected by a channel-electron-multiplier (CEM). The cone of the CEM was biased at +200V to accelerate the electrons to energies sufficient to liberate secondary electrons from the cone’s surface. The absolute efficiency $\varepsilon(E_e)$ of the CEM was modeled from a fit to the manufacturer’s measured data [11] as a function of the impact energy of the electrons on the cone.

The angular position of the analyzer/detector was set manually for each angle via a mechanical vacuum feed-through. At each angle, the acquisition of data for the energy spectrum was automated as follows. For each electron energy, the control computer calculated potentials for the analyzer electrodes. The computer sent the appropriate control voltages to the programmable power supplies that bias the electrodes. The projectile current to the Faraday cup was integrated, and electrons were counted for each data point until a specified cumulative charge of projectiles had been recorded.

C. Signals and Doubly Differential Cross Sections

The total number of electrons counted in a given run is

$$N_{e}(E_e, \theta) = N_p \varepsilon(E_e)\Delta E_e \left[ \int \Omega(z)dz \right] \left[ n_T \frac{d^2\sigma_T}{d\Omega dE_e} + n_R \frac{d^2\sigma_R}{d\Omega dE_e} \right],$$

where $N_p$ is the number of projectiles incident on the target during the run, $\varepsilon(E_e)$ is the absolute efficiency with which electrons are detected (a slowly varying function of the energy with which electrons strike the detector surface), $\Delta E_e$ is the full-width at half-max (FWHM) range of
electron energies admitted about \( E_e \): \( \Delta E_e = R \cdot E_{pass} = 0.05 \cdot (E_e + eV_a) \), \( E_{pass} \) is the kinetic energy of electrons inside the analyzer, \( V_a \) is the voltage on the accelerating electrode in the analyzer and \( z \) is the spatial coordinate in the direction of the projectile beam.

The terms \( n \) are the number densities of ‘target’ particles and the \( \sigma \) terms are DDCS for electron ejection. The subscripts \( T \) and \( R \) denote ‘target’ and ‘residual’ particles, respectively. The desired target gas in this case is the helium. However, there was always an additional component of the electron signal from the residual (background) gas in the vacuum chamber. The composition and absolute density of the background gas are unknown, as is the effective cross section for electron ejection in collisions with the carbon ions. To assess this contribution, we pumped the target gas out of the chamber and measured the electron signals from collisions of \( N_p \) projectile ions with the background gas. This measurement yielded the count of electrons produced by the residual gas:

\[
N_e^R(E_e, \theta) = N_p \varepsilon(E_e) \Delta E_e \int_\Omega(z)dz \cdot n_R \cdot \frac{\partial^2 \sigma^R}{\partial \Omega \partial E}.
\]

The number density of target atoms is \( n_T \ (cm^{-3}) = 9.65 \times 10^{15} \cdot \frac{P[mT]}{T[K]} \) (from the ideal gas law and the appropriate unit conversions). The number of electrons ejected in collisions of the ions with the target gas is similarly

\[
N_e^T(E_e, \theta) = N_p \varepsilon(E_e) \Delta E_e \int_\Omega(z)dz \cdot n_T \cdot \frac{\partial^2 \sigma^T}{\partial \Omega \partial E}.
\]

The DDCS for the target is the parameter we wish to measure because it is the only term in this expression that depends on the physical interactions of the ions with helium on the microscopic scale. This is also the parameter that will be predicted by theoretical calculations. We thus combine the various terms and solve for the cross section in terms of measured laboratory parameters:

\[
\frac{\partial^2 \sigma}{\partial \Omega \partial E} \left( \frac{cm^2}{sr \cdot eV} \right) = \frac{N_e(E_e, \theta) - N_e^R(E_e, \theta)}{N_p \cdot P[mT] \cdot e(E_e) \cdot (E_e + eV_a) [eV]} \cdot 1.645 \times 10^{-12}.
\]

These cross sections were measured and the results are plotted for each of eleven different angles from 15° to 160°, and several dozens of electron energies from 1.0 eV to a maximum of approximately 6.0 keV.

Corrections were made to the measured data to account for electrons scattered out of their trajectories toward the detector in collisions with the intervening target gas. The fraction of electrons reaching the detector was taken to be \( f = \exp\left[-n_T \sum l \sigma_s(E_i) \right] \), where \( n_T \) is the density of target atoms, \( l \) is the path length, \( E \) is the electron energy and \( \sigma_s \) is the total elastic scattering cross section at energy \( E_i \). The sum is over portions of the path in
which the electron has different kinetic energies (when accelerated or decelerated in the analyzer, e.g.). Values of the total cross sections for scattering of electrons by atomic helium were generated by numerical fits to the measured data of Golden and Bandel [12].

D. Singly Differential Cross Sections

Singly differential cross sections are generated by integration of the doubly differential results. The distribution of electron energies, without regard to the direction of their ejection is

\[ \int \int \frac{d^2 \sigma}{d \Omega dE_e} d\Omega = 2\pi \int \left( \frac{d^2 \sigma}{d \Omega dE_e} \right) \sin \theta d\theta. \]

Similarly, the singly differential cross section for ejection of electrons of any energy into solid angle \( d\Omega \) is

\[ \frac{d\sigma}{d\Omega} (\theta) = \int_0^\infty \left( \frac{d^2 \sigma}{d \Omega dE_e} \right) dE_e. \]

Experimental values for these parameters are obtained from numerical integration of the measured doubly differential cross-section data.

III. DATA AND RESULTS

The following graphs contain most of the measured data for DDCS versus electron energy, along with the results of the theoretical models (calculations by Dr. Laszlo Gulyás) used to predict the results. Each plot shows the spectrum for a different scattering angle. The theoretical models tested here are: Plane Wave (First-order) Born Approximation (FBA), Continuum Distorted Wave (CDW) and the CDW with an Eikonal Initial State (CDW-EIS).

A. DDCS for \( C^{5+} \) Impact

1. Energy Spectra

![Figure 3](image1.png)  ![Figure 4](image2.png)
2. Angular Distributions

Here we present some of the same data as functions of scattering angle for a few selected electron energies. The cross sections are expressed here in megabarns (1 Mb = 10^{-18} cm^2).

![Figure 11](image1.png)

![Figure 12](image2.png)

![Figure 13](image3.png)

![Figure 14](image4.png)

B. Singly Differential Cross Sections

Following are singly differential cross sections in energy and angle for both C^{5+} and C^{4+} impact. Notice the particularly good agreement of the data with CDW theory in each case (and with FBA for the energy spectra). This illustrates how sensitive the more detailed DDCS data are to the various theoretical models. Note that the FBA does not reproduce the data well in any of the angular distributions.
C. DDCS for C$^{4+}$ Impact

1. Energy Spectra
2. Angular Distributions

![Figure 25](image1)

![Figure 26](image2)

![Figure 27](image3)

![Figure 28](image4)

D. Theoretical Models

The three theoretical models represent varying degrees of approximation. All treat the projectiles as bare ions with an effective charge obtained from $E \approx \frac{Z_{\text{eff}}^2}{2n^2}$, where $E$ is the energy of the 1s orbitals on the Hartree-Fock-Slater potentials [14]. The resulting effective ion charges are 5.36 and 5.02 for C$^{5+}$ and C$^{4+}$, respectively [15]. Thus, only the target electrons are treated as active in each of these models.

The First Born Approximation (FBA) is the crudest of the models. It assumes that the projectile is scattered only by active target electrons (i.e. nucleus-nucleus interaction is neglected, an excellent approximation at the highly probable large impact parameters). Consequently, there is negligible distortion of the outgoing projectile wave and the ionization cross section depends on the charge and velocity, but not the mass of the
projectile. This assumption is typically valid when $Z_1/Z_2 \ll v_1/v_0$, where $Z_1$ and $Z_2$ are projectile and target nuclear charges, $v_1$ and $v_0$, the projectile speed and target electron Bohr velocity, respectively [16]. The present impact velocity is marginally high enough to satisfy this criterion.

The Continuum-Distorted-Wave (CDW) model is that of Belkić [17] in which wavefunction distortions are applied in both the initial and final channels. The Continuum-Distorted-Wave, Eikonal-Initial-State (CDW-EIS) results are obtained as an approximation to the CDW by replacing the distortions of the initial state by its asymptotic, eikonal form. Thus, the CDW is generally superior to the CDW-EIS. However, the CDW model tends to overestimate the electron yields at low projectile energies, due to the incorrect normalization of the CDW distorted waves. This normalization failure was corrected by an eikonal phase in the CDW-EIS model [18].

E. Spectral Features and Comparison of Data with Theory

All three theoretical models do a good job of reproducing the singly differential cross sections in electron energy (Fig. 15). Agreement of both CDW models is excellent also for the angle-differential cross sections (Fig. 16). The Born model fails to duplicate any of the angular distributions, but succeeds for the energy distributions, largely due to canceling errors. Thus, it is especially informative to compare all the models with the more stringent doubly differential cross-section data.

1. Soft Electrons

The vast majority of electrons ejected in ionizing collisions come from direct single ionization of the target atoms: $C^{n^+} + He \rightarrow C^{n^+} + He^+ + e^-$. These so-called 'soft' electrons are most numerous at very low energies. The agreement between data and CDW theory is generally very good, but the Born approximation fails to reproduce the angular distributions at essentially all electron energies (Figs 11-14, 16 and 25-28). Processes for which cross sections are large (low energy electrons ejected at all angles), may proceed at relatively large impact parameters where projectile electrons are not expected to participate in the interactions. Hence, the theoretical treatment of the projectiles as bare ions should be valid.

We expect the CDW model to give the best overall reproduction of the data since it employs the fewest simplifying approximations among the models tested here. Indeed, it gives excellent agreement with nearly all the data. The notable exception is the spectrum for $C^{4+}$ impact at $15^\circ$ (Fig. 17) where the data fall well below the theory at electron energies below about $100 eV$. Data and theory disagree even on the shape of this cross-section curve. While we are not surprised to see such a discrepancy for the very lowest electron energies ($\leq 10 eV$) due to the unknown effects of small stray fields, this spectrum is mysterious. The magnitude of stray electric or magnetic field necessary to deflect such relatively energetic electrons from their path is much greater than any we would imagine occupying the scattering chamber (from the earth or the steering magnets). All electrical leads inside the chamber were well shielded, and residual magnetic fields were measured
and found to be below 10mG everywhere in the chamber. Moreover, if stray fields were
the cause of this discrepancy, we would expect to see a similar pattern for the case of \( \text{C}^{5+} \)
impact, but we do not (Fig. 3).

2. Binary Encounter

The \textit{binary encounter (BE)} feature appears for all projectiles including bare ions [9] in
the electron energy spectra at forward angles. This is seen in figs. 4-7 and 17-21 and is
understood classically as the Rutherford interaction of the projectile nucleus with a quasi-
free target electron. Classical conservation of kinetic energy and momentum of a light,
free 'target' scattered elastically by a heavy 'projectile' predicts \( E = 4t \cos^2 \theta \), where \( t \) is
the kinetic energy of an electron with the velocity of the projectile: \( t = \left( \frac{m_e}{m_p} \right) E_p \). In the
present study the projectile velocity is \( 10 \text{ au} \) and \( t = 1361 \text{ eV} \). The cross section increases
rapidly with angle, reflecting the increasing probability of glancing collisions. As the
angle increases, the \( BE \) feature moves to lower energy and becomes larger until it
disappears into the soft electron continuum. The width of the \( BE \) peak is governed by the
Compton profile (distribution of \( z \) components of electron momentum) of the target atom.
It is fully resolved by the analyzer (\textit{i.e.} the data accurately reflect the natural width of the
peak with no apparatus limitation). Each of the theoretical models reproduces this feature
quite well.

3. Autoionization of Helium

A subtle but ubiquitous peak in essentially all the energy spectra appears at 34 eV. This
tiny bump on the large continuum of soft electrons arises from the decay of doubly
excited helium: \( \text{C}^{3+} + \text{He} \rightarrow \text{He}^* (2s2l) \rightarrow \text{He}^{+} + e^- (\sim 34eV) \). The energy at which this
peak appears does not vary with angle, indicating that the feature comes from target
atoms at rest in the laboratory reference frame. These electrons are nearly isotropic in
their angular distribution [13], and thus the feature is a bit more prominent at large
scattering angles where the cross sections for direct ionization are smaller (\textit{cf} Fig. 10).
This feature is not reflected in any of the theoretical models because they do not include
this manifold of inelastic scattering states. Also, the manifold of autoionizing states is
not resolved here.

4. Electron Loss to the Continuum

An important motivation for this extension of \textit{DDCS} data for bare carbon ion impact on
helium [9] was to investigate the extent to which projectile electrons would contribute to
the observed spectra. As expected, the agreement between theory and data for the
dominant low-energy (soft) electrons is excellent, where impact parameters are large and
the tightly bound projectile electrons do not participate in the interactions.

The measured data clearly indicate the presence of some scattered electrons originating
on the projectiles (Figs. 4-5, 17-24 and 28). Projectile electrons may be liberated into the
continuum in close interactions with target nuclei. This process, closely related to the \textit{BE} effect, is called Electron Loss to the Continuum (\textit{ELC}). It is essentially the Rutherford scattering of projectile electrons by target nuclei in the lab frame, where the cross section is strongly peaked in the forward direction and the energy of the ELC electrons is nearly independent of scattering angle. (The classical analogy is a light particle colliding with a massive one resulting in a scattered projectile of unaltered kinetic energy.) Equivalently, the process is a binary encounter in the projectile’s frame of reference.

At our collision speed of 10 \textit{au}, an electron has a kinetic energy of 50 \textit{au} = 1361 eV. As expected, the ELC feature appears at a lower energy than this due to the substantial binding energies of the projectiles: 490 eV and 392 eV [19] for \textit{C}\textsuperscript{5+} (1s 2S) and \textit{C}\textsuperscript{4+}, (1s\textsuperscript{2} 1S) respectively.

These high binding energies also imply very broad Compton profiles for these states. Since electrons in these orbitals are confined to such small volumes (spheres of radius approximately 1/6 \textit{au}), the uncertainty principle demands correspondingly wide distributions of momenta. This has the effect of broadening the feature in the laboratory frame because the \textit{z} components of the projectile electrons' velocities have a wide range of values with respect to the projectile nucleus. This translates into a wide range of projectile electron - target nucleus impact energies in the laboratory frame, and hence a very broad feature centered on the classically expected energy. In fact, the expected width of the ELC feature in energy space is so large that we expect to see only an enhancement (shoulder) on the continuum of soft electrons rather than a peak.

Nevertheless, Figs. 17 and 18 show an unmistakable peak at the appropriate energy. This suggests that there was a component of the \textit{C}\textsuperscript{4+} beam in an excited state, where the Compton profile is considerably narrower. The best candidate is the long-lived metastable 1s2s \textit{3S} state. The Compton profiles of the \textit{C}\textsuperscript{4+} states in question are shown in Fig. 29 below.

![Compton Profiles of \textit{C}\textsuperscript{4+}](image)

The fraction of the beam that was in the metastable state during data acquisition is currently unknown. Recently Zamkov \textit{et al} [20] have investigated metastable fractions in beams of \textit{B}\textsuperscript{3+} ions formed with both gas and thin foil stripping apparatus. Their results
suggest that the metastable fraction should be between 10% and 30%, but new data for carbon ions are clearly needed.

Further evidence that ELC electrons are, in fact being observed in the present data is seen in all the energy spectra for C⁴⁺ impact. In the backward direction, we see a tail of ELC electrons above the theory curves at the appropriate electron energy in figs. 22-24. Also, the ELC enhancement at electron energy 1.0 keV for all angles (except where the BE dominates) is dramatically evident in fig 28.

IV. CONCLUSIONS & RECOMMENDATIONS FOR FURTHER STUDY

The overall success of the CDW models in predicting these cross sections is striking. Where there is substantial disagreement (especially C⁴⁺ impact for electrons scattered at 15°) the data themselves are quite suspect. It is not particularly surprising that the FBA fares less well, but it is informative to quantify this where the impact energy is sufficiently high to satisfy its assumption of the validity of an impulse approximation.

Due to limited beam time, the spectra for C⁵⁺ impact were not carried to sufficiently high electron energy. Thus, we have incomplete information from them particularly about ELC electrons. It would be desirable to extend the measurements to fill this vacancy because we are certain that the C⁵⁺ beam consists entirely of ions in their ground state.

The metastable fraction of the C⁴⁺ beam must be measured and the ELC feature must be modeled theoretically for both C⁴⁺ and C⁵⁺ impacts. When these tasks are accomplished we will be able to correct the data to present cross sections for the impact of pure ground-state C⁴⁺ on helium. It will also provide a good test of the model(s) used to calculate the ELC contributions to the cross sections.

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