Ionization in fast-neutral-particle–atom collisions: H and He atoms impacting on He

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Experimental and theoretical data pertaining to the doubly differential electron emission occurring in collisions between structured projectiles and atoms are presented. How one or two loosely bound projectile electrons influence the ionization process was investigated for fast H- and He-atom impact on helium. Standard noncoincidence and ionized projectile–emitted-electron coincidence techniques were used to study the electron emission for 0.5- and 1-MeV/amu impact energies. The experimental data demonstrate the importance of events where both the projectile and the target are ionized in a single collision. From a comparison of theoretical calculations made using the first-order Born approximation and the experimental data, it is concluded that single ionization of the target and of the projectile are adequately described by such a model but that improved models are essential in order to account for the observed simultaneous projectile-target ionization events.

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I. INTRODUCTION

One of the most sensitive tests of theoretical models used to describe ionizing collisions is to compare experimentally and theoretically derived differential electron-emission cross sections. Past studies of this type have demonstrated that the first-order Born approximation can adequately describe single ionization occurring for fast proton impact on atomic targets [1]. In comparison, our current theoretical understanding of collisions involving projectiles possessing even a single bound electron of their own is rudimentary. Thus improving our understanding of interactions involving partially stripped ion impact is one of the next major steps in atomic collision studies.

Collisions involving partially stripped projectile ions are more complicated than their fully stripped ion counterparts because (1) loosely bound electrons can be ejected from either the target or from the projectile, and (2) in both cases the ionization is induced by a partially screened nuclear charge of the collision partner. An additional complication is that (3) during the collision it is possible for one of the collision partners to be singly, or multiply, ionized and the other to be singly, or multiply, excited to a discrete or a continuum state, i.e., a multiple electron-transition phenomenon [2]. Theory must model, calculate, and superimpose probabilities for each of these individual processes, whereas standard electron-emission measurements only provide information about the sum of these processes. Whether a coherent or incoherent summation is required in the theoretical treatment is an additional question.

In order to better test the individual components of the theoretical treatment, several years ago DuBois and Manson [2] used a projectile ion-electron coincidence technique (PIECO) to study the differential electron emission resulting from He^+ impact. They were able to obtain quantitative information about projectile, target, and simultaneous (meaning "in a single collision") projectile-target ionization events. These experimental data provide the opportunity to identify the successes and limitations of theoretical models used to describe partially stripped ion impact.

Prior to the present investigation, two studies of this type had been performed. In their original work, DuBois and Manson investigated electron emission in fast He^+-He collisions [2], but only for emission angles of 20° and 30°. From a comparison between experiment and theory, they concluded that the first-order Born approximation, when modified to account for electron screening of the nuclear charge and for simultaneous ionization-excitation events, could adequately describe ionization of the target and of the projectile. Simultaneous target-projectile ionization events were shown to be qualitatively handled but quantitatively were severely underestimated.

A more recent study by the same authors presented additional data for heavier targets [3]. In this study, data for an argon target were obtained for selected angles between 20° and 150°. When compared with theory, very poor agreement was found. This opened the questions: was the good agreement found for a helium target merely fortuitous because of the limited angular range studied?

Or was the poor agreement for argon primarily a wave-function problem? Or do inherent problems exist in the theoretical formulation? For example, their studies involved long-range Coulomb forces in the target ionization channel because the projectile was charged; but for projectile ionization no long-range forces were included in the theoretical treatment since the collision partner (the target) was neutral. Thus, was the theoretical treatment equivalent for target and for projectile ionization?

In order to answer these questions a series of experiments was performed at the Institute for Nuclear Physics, J. W. Goethe University in Frankfurt am Main, Germany, using standard noncoincidence as well as PIECO coincidence methods to study the differential electron emission occurring in *few-electron systems,* namely, H-He and He-He atom-atom collisions. In these systems, no long-range Coulomb forces exist for either target or projectile ionization; hence there is no "asymmetry" in the theoretical treatment. Also, by studying "simple systems," namely, fast-neutral-hydrogen- and -helium-atom impact on helium, any wave-function problems were circumvented. In addition, the capability of testing theory in detail was increased since the electron emission was measured for several angles in the range of 0°–50°.

Comparing these data with those obtained for H^+ impact yields information about the influence of one or two loosely bound electrons on the various ionization probabilities. Because of the simplicity of the systems studied and the detailed experimental data obtained by using the PIECO coincidence technique, a real opportunity for benchmark testing of theoretical models is available.

In a recent paper [4], a brief description of the H-, He-He data was presented for 0.5 MeV/amu impact energy and 30° electron emission. In this paper, theoretical cross sections obtained using a plane-wave Born approximation (PWBA) model with scaled hydrogenic wave functions indicated reasonably good agreement with experimental data for projectile ionization, and indirectly, for target ionization. It was thus suggested that the poor experimental-theoretical agreement previously found for the He^+-Ar system was largely owing to an inadequate description of the wave functions rather than any inherent errors in the theoretical formalisms used.

The present paper presents additional experimental data obtained for other angles and impact energies, thus providing a more complete picture of the ionization process. For a more thorough test of theory, additional theoretical PWBA cross sections are presented. A comparison of experiment and theory confirms the conclusions drawn from the 30° data, namely, that the PWBA formalism is capable of describing both target and projectile ionization.

II. EXPERIMENTAL APPARATUS AND TECHNIQUES

A schematic view of the experimental apparatus used in the present study is shown in Fig. 1. Data were obtained by crossing a directed helium gas target with a high-velocity beam of hydrogen or helium atoms and using a cylindrical mirror electron spectrometer to measure the emitted-electron spectra. The laboratory emission angles and energies studied ranged from 0 to 50° and roughly 20 to 1500 eV since counting rates outside these ranges were too small to be accurately measured using the present apparatus.

A. Production and detection of fast H and He beams

Energy analyzed He^+ and ${H_2}^+$ beams were passed through a section of beamline into which air was leaked. The beams were partially neutralized via charge capturing (for He-atom production) or dissociating (for H-atom production) collisions. The dissociation method was chosen for the production of fast H atoms since this method produced more intense beams at higher energies than could be obtained via charge capture by fast protons. After neutralization and prior (≈ 1 m) to the target interaction region, the charged components of the beams were removed by a 1-kV/cm electric field applied perpendicular to the beam direction. For H impact this field also quenched any long-lived metastable states.

For He impact an additional electric field (approximately 8.5 kV/cm) was applied roughly $\frac{1}{2}$ m before the 1-kV/cm field, the background gas pressure was increased to 0.05 mbar in the region between the two electric fields, and the pressure in the region of the final field was raised to 0.08 mbar. These measures were taken in order to help eliminate any excited 2*s* states in the incoming He beam. When the 8.5-kV/cm field was turned on, the 0° electron-loss peak intensity was observed to decrease approximately 20%; no differences were observed for field strengths in the range of 6.5–8.5 kV/cm; smaller fields were not tested.

For the fields quoted, we are reasonably confident that the H beam consisted of more than 99% ground-state hydrogen atoms [5]. However, using pressure and dimension parameters for the present apparatus and data relating to ground-state and excited-state cross sections for He impact [6], the surviving metastable component of the He beam at the target was estimated to be as large as 35–40 %. Using the ground- and excited-state cross-section data of Pedersen *et al.* [6], we estimate that the *total* electron-loss cross sections measured in the present experiment could be 20–25 % too large because of the surviving metastable beam component. We are uncertain how this would affect the *differential* cross sections but we note that as the first quench field was turned on we observed a decrease in the differential electron-loss cross sections. The observed decrease was roughly consistent with the decrease in the *total* loss cross section that Pedersen *et al.* measured as they decreased the metastable component of the He beam to *zero.* This could imply that we were successful in removing all metastable contributions to the He-He cross sections reported here; or, in the worst case, namely, a surviving He metastable fraction of 40%, we estimate that the He impact differential cross sections reported here could be as much as 20–25 % too large.

The neutral projectiles were detected by two different methods depending on whether a singles (noncoincidence) or coincidence measurement was being per-

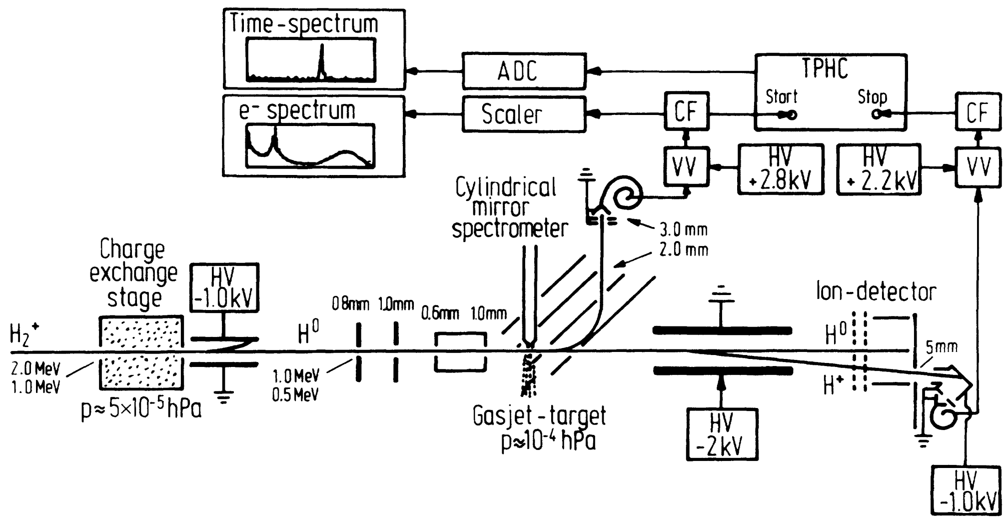

FIG. 1. Schematic view of experimental apparatus and electronics.

formed. For the singles measurement, the neutral projectile beam was stripped in a thin (20 μg/cm^2) carbon foil located directly after the target chamber and the emerging H^+, He^+, or He^{2+} currents were collected in a biased Faraday cup. The stripping efficiency of such a foil is known [7] and hence the absolute neutral beam intensity could be determined by measuring the currents.

For the coincidence measurement, a postcollision electric field deflected the ionized component of the beam onto a secondary electron-emission beam detector [8]. The measured intensities were approximately $(2-5)\times 10^5$ sec^{-1} with target gas and roughly a factor of 10 smaller without target gas. The detection efficiency was determined at each electron-emission angle and impact energy by comparing electron counting rates measured in the coincidence and singles experiments. For this comparison, only the rates near the maximum of the electron-loss peak were used since in this region the electron signal is predominantly owing to projectile ionization.

Results for the projectile detection efficiency measurements are as follows. For H impact, an efficiency of 0.45±0.15, averaged for all emission angles and impact energies, was obtained. For He impact, the measured efficiency was found to decrease with electron-emission angle. It ranged from approximately 50%, using the 0° emission data, to approximately 26%, using the 30° data. We do not understand this variation in the measured efficiencies but doubt that it is related to the electron-loss intensity which also decreases with increasing angle, i.e., to the electron signal intensity used in determining the projectile detection efficiency. Nor do we believe that scattering losses are contributing to inaccurate measurements at the larger emission angles. Thus, for He impact, the actual efficiencies measured at each angle were used in determining absolute cross sections.

B. Electron detection

An electron spectrometer, similar to that described by Bernardi *et al.* [9], was used. The input and exit apertures were chosen to maximize the electron counting rate while still maintaining a reasonably good energy and angular resolution, e.g., $\Delta E/E=0.03$, $\Delta\theta_e=1.67°$. The spectrometer was aligned to the target-beam intersection by externally adjusting the θ and ϕ orientation in order to maximize the electron counting rate at 0°. Then the 0° (θ) electron-emission angle was determined with an accuracy of ±0.25° by monitoring the electron-loss intensity for positive and negative angles and assuming symmetry around zero.

C. Normalization procedure

In order to place the H and He impact data on an absolute scale, the electron detection efficiency as a function of electron-emission angle and energy and the target gas density were determined via a normalization process. Doubly differential electron emission was measured for proton impact and the measured differential electron-emission signals were normalizing to the absolute cross sections of Rudd, Toburen, and Stolterfoht [10].

The coincidence data were then normalized to the noncoincidence data by using the electron-emission intensities measured during the singles and the coincidence experiments. For this normalization only data near the maximum of the electron-loss peak were used since in this region the electron intensities were largest.

Fluctuations in the target gas pressure could be monitored during the data accumulation process by detecting scattered projectile ions with a surface barrier detector. For H impact, this method was used to confirm the beam normalization at various angles; for He impact, the scattered projectile signal was too weak to be used.

Owing to the normalization procedures and uncertainties in the metastable components of the He beam, uncertainties in the *absolute* cross sections are conservatively estimated to be approximately ±50%. However, relative uncertainties for data obtained for different projectiles and angles are smaller—approximately ±20% in the region of the electron-loss peak where statistical uncertainties are small and ±50% or larger for electron energies below 50 eV and in the binary encounter region where statistical uncertainties are large.

Standard electronics were used to process the projectile and target signals with the processed data being stored List Mode in a computer. Electron spectra were accumulated in roughly 1.5- or 3-eV steps for the singles measurement and in 13-eV steps for the coincidence measurement. Statistical uncertainties for the coincidence data were reduced by averaging adjacent data points and plotting the results at the averaged energies. This introduces some uncertainty into the lowest-energy points; hence no coincidence data below 30 eV are shown.

III. THEORETICAL CALCULATION OF THE DOUBLY DIFFERENTIAL CROSS SECTIONS

One of the primary goals of this work is to provide data capable of detailed testing of various theoretical models. Although total [11,12] and singly differential [13] cross sections have previously been calculated, we are aware of no published theoretical calculations of the differential electron emission for fast H and He impact. Thus we have performed PWBA calculations as outlined by Rudd and Macek [14] and have determined doubly differential cross sections for the experimental parameters studied here.

The theoretical treatment used scaled hydrogenic wave functions for describing both the target and the projectile. Screening of the nuclear charge by the bound projectile (target) electron(s) was handled by using an effective projectile charge that depends on the momentum transfer [15], $Z_{\rm eff}(q)$. Electron emission resulting from projectile ionization was calculated in the projectile rest frame and then transformed into the laboratory frame following the procedure described by Drepper and Briggs [16]. The PWBA formulation used is valid for single electron transitions only; hence simultaneous target-projectile ionization probabilities were not determined. We recognize that other, more sophisticated, theoretical treatments exist [3] but our primary intent is to demonstrate where future theoretical models might encounter problems.

IV. RESULTS

Absolute doubly differential cross sections were measured at selected angles between 0° and 50° for 0.5-MeV/amu H^+, H, and He impact and for 1-MeV H^+ and H impact. In all cases, data for the total electron emission were obtained using noncoincidence techniques; for H and He impact, projectile ion-electron coincidence techniques were also used in order to identify contributions from projectile and simultaneous target-projectile ionization. For He impact both the single- and double-loss channels for projectile ionization were investigated.

A. H impact

1. Singles data

In Fig. 2 data for 0.5- and 1-MeV H impact are compared with those obtained for H^+ impact in order to

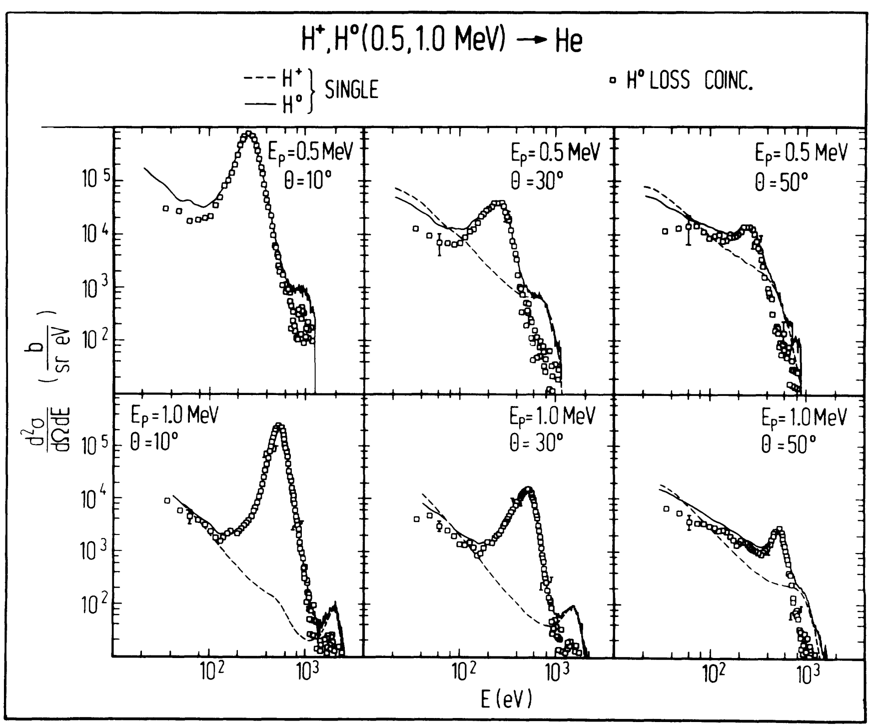

FIG. 2. Cross sections for 0.5- and 1-MeV H-atom and H^+ atom impact on He. Singles (noncoincidence), — — — and ——, and projectile ion-electron coincidence (PIECO), □, measurements.

demonstrate how a single, loosely bound projectile electron influences the electron-emission spectra. The H^+ impact data demonstrate the well-known monotonic decrease in the target ionization cross section for increasing ejected electron energy and a "binary encounter peak" located at an electron energy given by $4T\cos^2\theta$, where T is the reduced impact energy, i.e, $T=Em/M$, m and M being the electron and projectile masses, respectively. For 10° emission, a small electron capture to the continuum contribution can be seen at electron energies matching the reduced projectile energy T.

For H-atom impact, two major differences in the spectra occur. First, an intense peak located at T, resulting

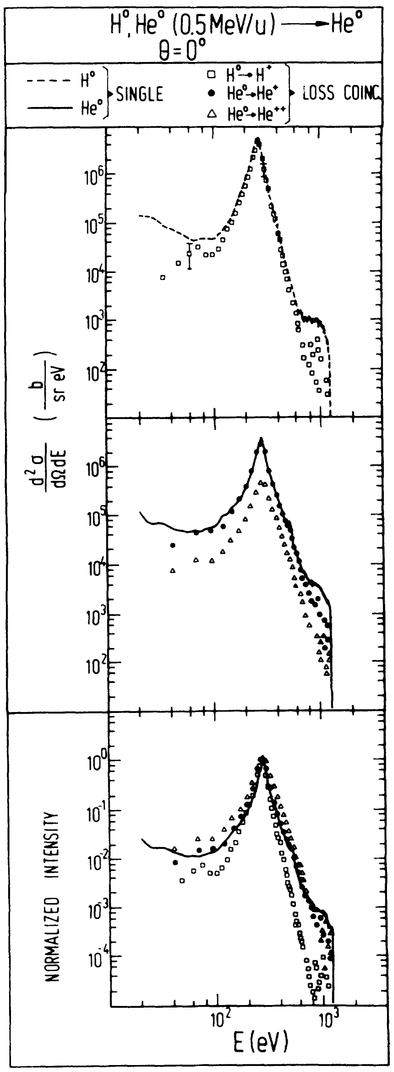

FIG. 3. Electron emission at 0° for 0.5-MeV/amu H- and He-atom impact on He. Singles (noncoincidence) cross sections: — — —, H impact; ——, He impact. PIECO (coincidence) cross sections: □, single loss from the H projectile; ●/△, single/double loss from the He projectile. In the lower portion of the figure the singles data for He impact and the coincidence data for H and He impact have been normalized to unit intensity at the maximum of the electron-loss peak in order to demonstrate how the width of the peak depends on the binding energy of the ionized projectile electron.

from ionization of the 1*s* projectile electron, is seen. Since the majority of the ionized projectile electrons have small kinetic energies in the projectile frame, the kinematic transformation to the laboratory frame produces a peak centered at the projectile velocity and having a width indicative of the momentum distribution of the ionized projectile electron. The intensity of the peak is the differential cross section for projectile ionization and is similar to the differential elastic scattering cross section for electron impact [17].

The second major difference for H impact can be attributed to screening of the projectile nuclear charge by the bound 1*s* electron. For large-impact-parameter collisions which are responsible for the low-energy end of the emitted-electron spectra the screening of the nuclear charge reduces the cross section for H impact with respect to that for H^+ impact. For small-impact-parameter collision where the screening is ineffective [15,18], the H cross sections are expected to be similar to the incoherent sum of the cross sections for H^+ and e^- impact [15]. However, the incoming (projectile) electron has the projectile velocity. Hence the maximum energy of an ionized target, or scattered projectile, electron is T, the reduced projectile energy. Thus for electron energies larger than T, i.e., above the electron-loss peak, the cross sections for H and H^+ impact are expected to be the same. The data in Fig. 2 demonstrate these features.

2. *Coincidence data*

Using the PIECO coincidence technique, additional information about projectile and target ionization can be obtained. These data, indicated by the open squares in Fig. 2, confirm that the peak centered at the projectile velocity does indeed result from ionization of the projectile. More important, they demonstrate that this peak sits on a continuous background extending to electron energies above and below the peak. This background was identified by DuBois and Manson [2] as resulting from events where both the target and the projectile are ionized in a single collision. The relative importance of these "simultaneous ionization" events with respect to the total electron emission at each angle is larger for electron energies less than T than in the binary encounter region. Also the relative importance appears to increase with impact energy.

B. He impact

1. *Singles data*

The data for H impact provide information about the influence of a single loosely bound projectile electron on the ionization probabilities. The next step in understanding clothed particle impact is the influence of a second loosely bound projectile electron. Thus data for 0.5-MeV/amu He impact were measured and are presented in Figs. 3 and 4. Laboratory electron-emission angles of 0° and 10° are shown. Cross sections for 30° electron emission have been presented in a previous paper [4] so are not graphically included here. The figures also contain data for H impact for comparison purposes.

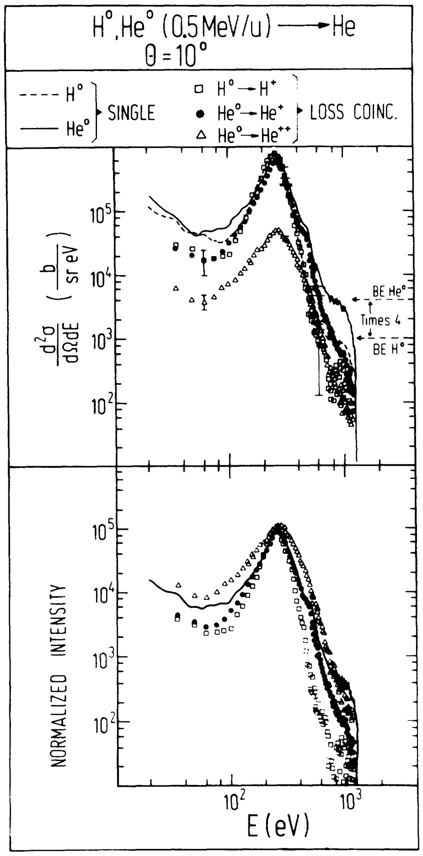

FIG. 4. Same as for Fig. 3 except for 10° emission angle.

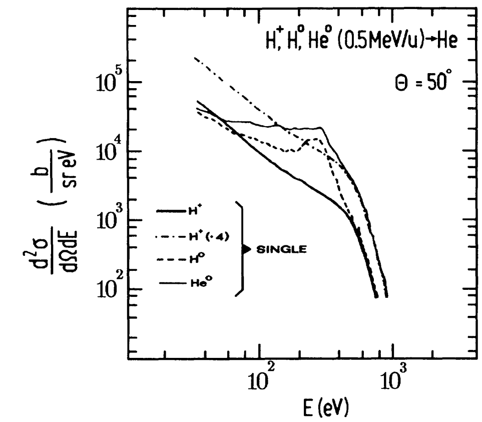

FIG. 5. Singles (noncoincidence) cross sections for electron emission at 50° in H^+, —— He^{++} (as approximated by four times the H^+ cross section), —·—·—·, H-atom — — —, and He-atom, ——, impact.

For electron emission at 50°, it was not feasible to obtain coincidence data because of decreasing cross sections and limited He beam intensities. Hence only singles (noncoincidence) data are shown in Fig. 5. The data are for H, He, H^+ , and He^{2+} impact which was approximated by four times the proton impact cross sections. The data clearly demonstrate that in the binary encounter region the cross sections for H^+ and H impact are identical as are the cross sections for He^{2+} and He impact. They also demonstrate the reduced cross sections for low-energy electron emission resulting from structured projectile impact with respect to fully stripped ion impact. These feature are as expected.

2. Coincidence data

For He impact, information about the contributions of single and double projectile ionization events to the electron-emission cross sections was obtained by the PIECO coincidence method. These data are shown in Figs. 3 and 4. In the region of the electron-loss peak where projectile ionization dominates the electron spectra, the double-loss cross sections are roughly a factor of 10 smaller than the single-loss cross sections. Thus the ratio of double to single ionization for He-He collisions is considerably larger than was measured for isotachic H^+ , H, or He^+ impact on He [19–22].

However, for smaller electron energies and in the binary encounter region, where *simultaneous projectile-target ionization* is important, a different ratio is found. For example, at 0° and 10° the coincident cross sections associated with double ionization of the projectile are only a factor of 4 smaller than the coincident cross sections associated with single ionization of the projectile; at 30° they are roughly a factor of 7 smaller. Thus it is roughly a factor of 10 less likely that the projectile will lose two electrons rather than a single electron, but, should it lose two electrons, it is more likely that the target will be ionized and it is likely that the target electron will be emitted *in the forward direction.*

C. Comparison of the H and He impact data

1. *Width and intensity of the electron-loss peak*

If we compare the He and H impact spectra some similarities and some differences are noted. One of the differences is the width of the electron-loss peak which increases as the momentum of the bound electron that is ionized increases. Thus the peak is broader for He double loss than for He single loss, which is, in turn, broader than for H single loss. This is demonstrated in the lower portions of Figs. 3 and 4 and Fig. 1, Ref. [4], where the respective electron-loss peaks have been normalized to unity at the peak maxima.

Comparing the width of the electron-loss peak for the coincidence and the singles data demonstrates that when the projectile ionization probabilities are large with respect to the target ionization probabilities, e.g., for small laboratory angles, the electron-loss peak shape is predominantly influenced by the momentum distribution of the more weakly bound electron; when the probabilities become more comparable, e.g., for larger emission angles, the peak shape is strongly influenced by the velocity distribution of the more tightly bound projectile electron. For example, at 30° the shape of the singles electron-loss peak is nearly the same as that measured for double electron loss from the projectile but at 0° it is nearly the same as that measured for single electron loss from the projectile.

The intensity of the electron-loss peak as a function of laboratory emission angle shows that at 0° it is approximately 50% more probable to singly ionize H than He, at 10° the probabilities are nearly equal, but at 30° and 50° (see Fig. 5) it is approximately 60% more probable to ionize He than H. It is know [23] that the total single-loss cross sections for He impact on He are approximately 60% larger than the single-loss cross sections for H impact [24]. The present data, when integrated over angle, show that the total cross section is dominated by contributions for angles around 30–50° due to the $\sin\theta$ term in the integration coupled with rapidly decreasing intensities for larger angles. Hence the 30° and 50° data yield a larger total electron-loss cross section for He impact while the 0° data would imply that the H impact cross section is larger. The message to be derived from this is that conclusions about total cross sections for projectile ionization that are obtained from measurements made only at 0° can be erroneous.

2. *Binary encounter region*

In the binary encounter region, the data in Figs. 3 and 4 demonstrate interesting relationships between the various coincidence and singles cross sections. Figure 2 showed that, in the binary encounter region, for H-He impact the coincidence (simultaneous ionization) cross sections are small with respect to the singles (simultaneous plus target ionization) cross sections. Hence the H-He binary encounter data originate primarily from a collision where a single electron is removed from the target. Figures 3 and 4 show that this occurs with approximately the same probability as a collision where one electron is removed from a He projectile *and* an electron is removed from the target, i.e., the H impact singles cross sections and the He impact single-loss coincidence cross sections are identical. Thus a binary collision between a target electron and an incoming H atom predominantly leads to removal of the target electron. This process has an identical probability as a binary collision between a target electron and a He atom where *both* collision partners are ionized.

We also observe that the coincidence double-loss cross sections for He impact are identical with the coincidence single-loss cross sections for H in the binary encounter region, i.e., the probability of a binary collision that removes two electrons from a He projectile *and* an electron from the He target is the same as the probability of removing an electron from both particles in a H-He collision. Considering that these processes represent two and three electron transition events, it will take a sophisticated theoretical treatment, possibly including electron correlation, to explain these observations.

D. Comparison with PWBA theory

One of the primary purposes of the present study is to test our theoretical understanding of electron emission resulting from clothed projectile impact. To date, no doubly differential cross sections for the present collision systems have been published. Thus, using a PWBA theory with scaled hydrogenic wave functions, we have

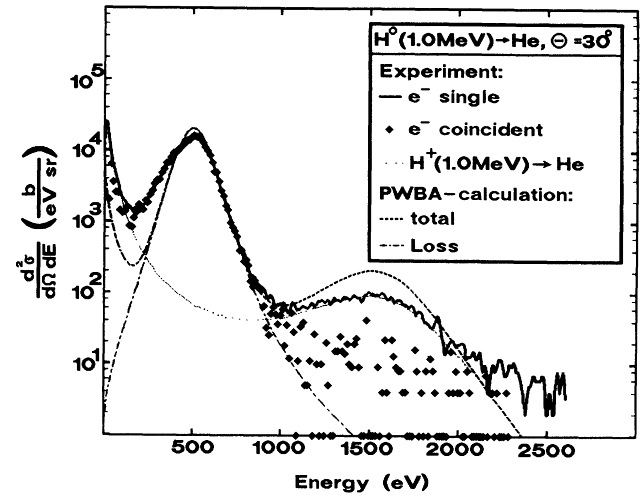

FIG. 6. Experimental and theoretical cross sections for differential electron emission in 1-MeV H-He collisions. The theoretical model used the first-order Born approximation as outlined in Ref. [11]. See text for details. Experiment: ——, noncoincidence electron emission; ♦, ionized projectile-electron coincidences. · · · ·, target ionization for H^+ impact. Theory: — — —, total (sum of target plus projectile) ionization; —·—·—·, projectile ionization.

calculated cross sections for single ionization of the target and of the projectile for H and He impact on helium. Although the previous studies of DuBois and Manson [2,3] have demonstrated the limitations of using the first-order Born theory for fast He^+ impact, similar tests for collisions involving fast-neutral-particle impact have not previously been possible.

In a recent paper [4], experiment and PWBA theory were compared for 30° electron emission in 0.5 MeV/amu H-He collisions. From this comparison, it was concluded that the PWBA theory could adequately describe single ionization of the projectile and of the target. Simultaneous target-projectile events were not included in the theoretical model although the experimental data demon-

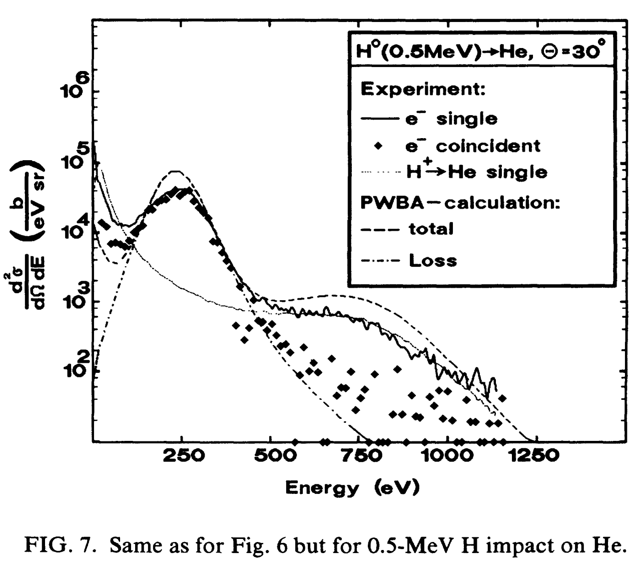

FIG. 7. Same as for Fig. 6 but for 0.5-MeV H impact on He.

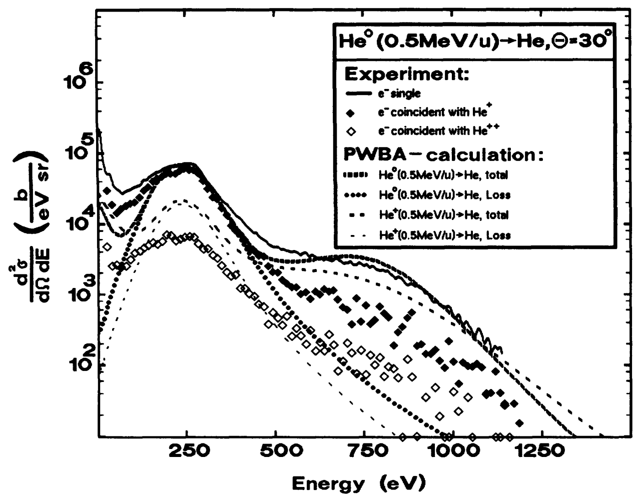

FIG. 8. Experimental and theoretical cross sections for differential electron emission in 0.5-MeV/u He and He^+ impact on He. Experiment: He impact; —— , noncoincidence electron emission; ♦, electron-He^+ coincidences; ◇, electron-He^{2+} coincidences. Theory: ■■■ and — — —, total electron emission for He and He^+, respectively; · · · · and — — —, single projectile loss cross sections for He and He^+ impact.

strate the importance of such events in these collisions.

Experiment and theory are compared for 1-MeV H and for 0.5-meV/amu H and He impact in Figs. 6–8, respectively. At 1 MeV, PWBA theory describes projectile ionization (loss) very well. In the binary encounter region, target ionization is overestimated by a factor of 2. The absence of simultaneous ionization events in the theoretical treatment results in a drastic underestimation of the cross section for electron energies less than 400 eV. These simultaneous ionization events account for the difference between the experimental single electron-loss coincidence cross sections, ♦, and the PWBA total cross sections (— — —). If this difference were added to the PWBA total cross sections, good agreement with the measured total differential cross sections would result. Hence we conclude that target ionization is also handled reasonably well by PWBA theory.

For 0.5 MeV/amu, theory overestimates projectile ionization but, using the same arguments as above, target ionization again appears to be handled reasonably well. Figures 7 and 8 indicate that there is no major difference between the ability of theory to handle single ionization for H and He impact. Thus the overall messages to be derived from the comparison between experiment and theory are (1) the problems previously noted for He^+-Ar collisions are probably attributable to inadequate wave functions used in the theoretical treatment rather than any inherent problems in the theoretical model and (2) for any theory to be able to describe clothed ion impact, simultaneous target-projectile ionization or excitation events *must* be included. Whether these simultaneous events require a correlation treatment is yet to be determined.

V. CONCLUSIONS

Cross sections for electron emission resulting from projectiles having one and two loosely bound electrons, namely, H and He, impacting on helium have been presented. By comparing these data with those obtained for a fully stripped projectile, H^+, insights into how loosely bound projectile electrons influence ionization were obtained. Comparing the experimental data to PWBA calculations was done in order to guide future theoretical treatments of such collisions.

This study has shown the importance of simultaneous projectile-target ionization events in these collisions. In the projectile single ionization channel, simultaneous projectile-target ionization events have a larger relative importance in the low-energy end of the electron spectra than in the binary encounter region. Interesting, but unexplainable, relationships between the various coincidence and noncoincidence cross sections were also noted in the binary encounter region. It was observed that the differential electron-loss cross section for He impact is larger than for H impact only for large laboratory emission angles; at small angles the reverse is true.

PWBA calculations appear to adequately describe target and projectile emission occurring in these collisions. Simultaneous ionization events were not included in the theoretical treatment although the experimental data overwhelmingly demonstrate that this is required. From the comparison we conclude that the poor agreement demonstrated previously for He^+-Ar collisions is probably attributable to inadequate wave functions used for describing the argon target. Hence the basic theoretical treatment used was probably adequate for describing single ionization events.

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