Energy and Angular Distributions of Electrons from Fast He$^+$+He Collisions

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The first realistic calculations of the energy and angular distributions of electrons ejected in ion-atom collisions, where the ion carries along its own electrons, are presented. The calculations, within the Born-approximation framework, have been performed for He$^+$ + He collisions, and measurements have also been made. Rather good quantitative agreement between our measurements and calculations has been obtained over a broad range of energies and angles. Some difficulties persist, however, near the forward direction.

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The study of the ionization process in ion-atom collisions in which the ion carries its own electrons is of importance in a number of diverse areas. Most of the work extant deals with total cross sections; however, far more information on ionization mechanisms and other details of the collision process may be derived from the study of the energy and angular distribution of the ejected electrons (double-differential cross section). In this paper, we present the first realistic calculations of such an ion-atom collision presently amenable to experimental investigation, along with our measurement. For simplicity we have chosen He$^+$ +He for this prototype theoretical and experimental study since the He target has only a single subshell and the He$^+$ projectile is a hydrogenic system.

The measurements were performed using methods described in detail elsewhere.[1] The calculations were done within the framework of first Born approximation, which has proven satisfactory for the description of energy and angular distributions of electrons ejected from He by structureless charged particles.[2]

There are several aspects of the He$^+$ +He collision which differ from the He^{++} +He or H$^+$ + He cases. First is the fact that the projectile electron screens the projectile nuclear charge. Within the Born approximation the double-differential cross section (DDCS) for ejecting an electron of energy ϵ by the screened He$^+$ ion[3,4] is given by

$$\frac{\partial^2\sigma}{\partial\epsilon\,\partial\Omega}=\int_{K_{\min}}^{K_{\max}}\left\{2-\frac{1}{[1+(Ka_0/4)^2]^2}\right\}^2 I(K)\,dK, \qquad (1)$$

where K is the momentum transfer, a_0 is the Bohr radius, and $I(K)$ is a complicated function of radial matrix elements and phase shifts.[2] The expression in brackets is the screening function; without this expression, Eq. (1) would be relevant to ionization by H$^+$. The expression in brackets can be thought of as the effective charge of the projectile and is seen to vary between 1 and 2 for small and large momentum transfer, respectively. Note that the screening is a function of momentum transfer K and *not* energy transfer[3] which is an integral over K as seen in Eq. (1).

An example of the theoretical results for the ionization of He by equal velocity H$^+$, He$^+$, and He^{++} ions is shown in Fig. 1 for electrons ejected at 60° to the incident ion; for this comparison the He$^+$ ion was assumed to remain in the ground state. The cross sections for He^{++} are just a factor of 4 times the values for H$^+$ since the Born cross sections for bare ions scales as z^2. The He$^+$ results, on the other hand, behave similar to H$^+$ for small energy transfer (which involves primarily small momentum transfers) and like He^{++} at large energy transfers for which large K predominates. Basically, this means that for small ϵ, He$^+$ acts like a heavy proton while for large ϵ it behaves like an α particle insofar as the ionization of the target is concerned.

One could, in principle, derive an effective z, as a function of ϵ, from these results. This effective z, however, is a function of angle as well as ejected electron energy. We find that the manner in which the He$^+$ results vary in progressing from H$^+$-like at low energy to He^{++}-like at high energy differs, in detail, from angle to angle. In addition, the above results, although they include screening, do not take into account the possibility of target ionization and *simultaneous* projectile

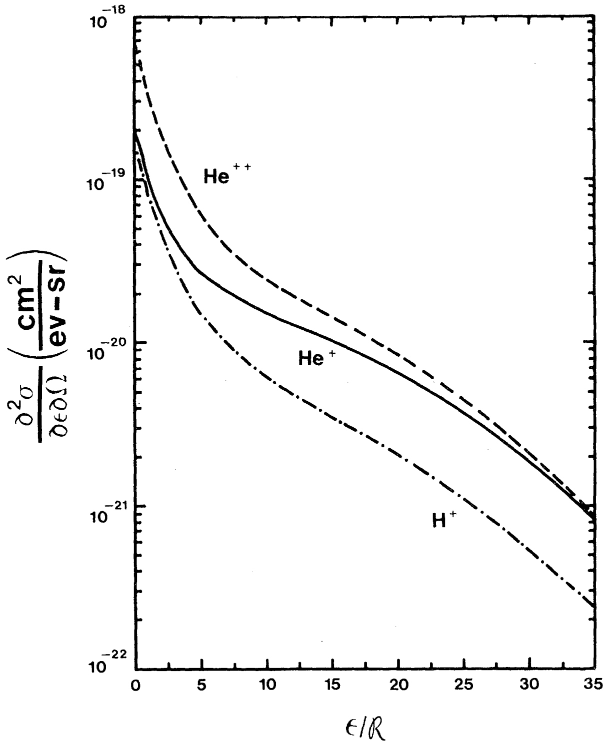

FIG. 1. Theoretical double-differential cross sections for ionization of He by equal velocity H^+, H^{++}, and He^+ (target ionization only with no projectile excitation) as a function of ejected electron energy ε (in rydbergs) at an ejection angle of 60°. The incident velocity corresponds to 0.5-MeV H^+, and 2.0-MeV He^+ and He^{++}.

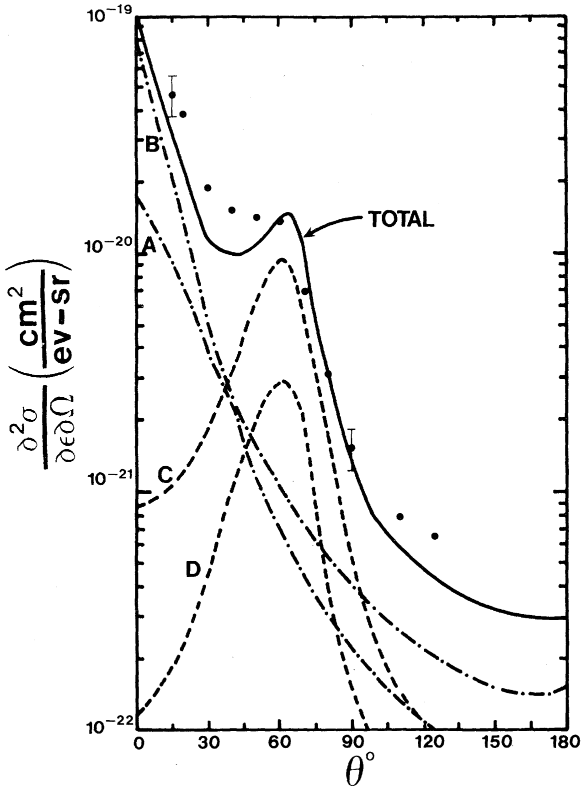

FIG. 2. Double-differential cross section for ejecting electron of energy 16 Ry by 2-MeV He^+ incident on He. The points are experimental; the solid curve is the theoretical result which is the sum of the cross sections: line *A*, projectile ionization, target remains in ground state; line *B*, projectile ionization with simultaneous target excitation; line *C*, target ionization, projectile remains in ground state; and line *D*, target ionization with simultaneous projectile excitation.

excitation. Furthermore, since DDCS measurements to date have not distinguished electrons ejected from the target from those originating from the projectile, contributions from projectile ionization must be included in the theoretical calculations.

We have, therefore, extended our calculations to include contributions from target ionization with possible simultaneous excitation of the projectile as well as contributions of the projectile ionization with simultaneous excitation of the target. Excitation is included via an approximate sum rule.[4] Projectile ionization is calculated in the rest frame of the projectile and transformed to the laboratory frame as discussed by Drepper and Briggs.[3] It is important to note that the cross section for electron ejection processes which occur in the projectile frame, e.g., projectile ionization, will tend to maximize for zero-energy secondary electrons.[2-5] As seen in the laboratory frame, these electrons will be sharply peaked in the forward direction, as well as peaked around a velocity equal to the projectile velocity, simply because of the frame transformation.[3,4] This velocity matching for incident 1.2- and 2.0-MeV He^+ projectiles occurs for electron ejected with energies approximately 12 and 20 Ry, respectively, in the laboratory frame. The result of our calculation for a typical angular distribution near the velocity-matching energy is shown in Fig. 2 along with our measured cross sections. From this figure it is seen that theory and experiment are in rather good agreement both qualitatively and quantitatively. The peak at ~ 60° is due to target ionization and, as seen from Fig. 2, most of the contribution arises from ionization with the projectile left in the ground state; target ionization with simultaneous projectile excitation is only a very small fraction of the total for all angles.

The peak at 0° in Fig. 2 arises primarily from projectile ionization. This contribution is dominated by projectile ionization with simultaneous target excitation. Figure 2 also shows that the situation is reversed for the backward angles; here simultaneous excitation is only of minor importance. This is, in essence, an energy-dependent effect wherein low-energy projectile electrons (in the projectile frame) issue forth primarily with simultaneous target excitation while high-energy electrons ejected from the projectile are associated chiefly with the target remaining in the ground state; in the case shown in Fig. 2, projectile electrons observed at the forward angle (in the laboratory frame) result from low-energy electrons ejected in the projectile rest frame, while the large-angle ejected electrons arise from much higher energies, because of the frame transformation.[3,4]

The major quantitative discrepancy between theory and experiment occurs at about 40°, which is between the two peaks where the calculation predicts a valley but the experiment does not show one. It is also evident from Fig. 2 that the theoretical cross sections are somewhat low at both the very small *and* the very large angles, regions which are dominated by projectile ionization. It may be that the Born approximation for the ionization of the projectile (He^+) by a neutral (He^0) is inadequate at these energies, or that the Hartree-Slater wave functions employed for the He^0 are not sufficiently accurate to describe the screening properly in the ionization of the projectile by the target. Charge transfer to the continuum is also ignored in the calculation, and this could be significant for forward angles. No real change in the discrepancy is seen in going from 1.2 to 2.0 MeV, but this may just be too small an energy interval; it would be interesting to see if the differences disappear (or decrease) for, say, 10-MeV He^+ impact.

In conclusion, then, we have presented experimental results along with the first realistic calculations of the DDCS in structured ion-atom collisions and have obtained fairly good quantitative agreement. Some problems, as described above, still remain, and these are being investigated.

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[1] L. H. Toburen and W. E. Wilson, Phys. Rev. A 19, 2214 (1979), and references therein.

[2] S. T. Manson, L. H. Toburen, D. H. Madison, and N. Stolterfoht, Phys. Rev. A 12, 60 (1975).

[3] F. Drepper and J. S. Briggs, J. Phys. B 9, 2063 (1976).

[4] J. S. Briggs and K. Taulbjerg, in *Topics in Current Physics 5: Structure and Collisions of Ions and Atoms*, edited by I. A. Sellin (Springer-Verlag, Berlin, 1975), pp. 105–154.

[5] M. E. Rudd and J. H. Macek, Case Studies At. Collision Phys. 3, 47 (1972).