Low-energy electron emission in proton-helium collisions

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We have measured doubly differential cross sections for slow electrons emitted in collisions of H^+ on He at 100 and 200 keV. The electron energy comprised the range from 1 to 16 eV. We present a detailed account of the experimental steps followed in order to obtain confidence in the data. Two features in the angular distribution of the low-energy electron emission were observed: a strong forward-backward asymmetry that gets smaller at higher projectile energy, and a minimum around $\theta=120°$.

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Since the pioneering work of Rudd and co-workers, from 1963 up to now many laboratories have furnished experimental information about doubly differential cross sections for electron emission in ion-atom collisions [1]. Such measurements covered nearly the full range of electron energies and angles, including electron energies of the order of 1 eV. It is known that the main contribution to the ionization process, which originates from "soft" (or glancing) collisions, is found in the region of low electron energies. Measurement of these low-energy electrons involves serious experimental difficulties. Toburen and Wilson have used a time-of-flight technique [2] in order to improve the measurement in this range. Generally, due to limitations in the accuracy of measurements, little attention has been paid to the "soft-electron" emission (SEE), until recent measurements performed in our laboratory showed that a quantitative discussion was possible [3,4]. The most striking evidence was a strong forward-backward asymmetry that was also found to be consistent on a theoretical basis and with other published experimental data [5]. This asymmetry is expected to become smaller with increasing projectile energy, until at a sufficiently high energy it is supposed to reach the limit of the optical dipole anisotropy [6].

The doubly differential cross section $d\sigma/d\mathbf{v}$, for soft electrons is dominated by a $1/v$ divergence in the limit $\mathbf{v}\to 0$. This divergence is due to the normalization factor in the Coulomb wave function describing the state of the electron lying in the low continuum of the ionized target atom. Another structure in the cross section, described by a similar divergence when $\mathbf{v}\to\mathbf{v}_p$, with $\mathbf{v}_p$ the projectile velocity, is the electron capture to the continuum (ECC) peak [7]. This process is appropriately described as a capture mechanism that implies large momentum transfer, of the order of $\mathbf{v}_p$, to the emitted electron. An essential feature is the asymmetry of the ECC peak, that is due to a perturbation of the electron captured into the projectile continuum, by the Coulomb field of the residual target ion. In an analogous sense the asymmetry observed in the soft-electron emission is attributed to the perturbing action of the ionic projectile [3,4]. In the region between $\mathbf{v}=0$ and $\mathbf{v}=\mathbf{v}_p$ the asymmetries of the SEE and ECC peaks merge into a broad ridge-shaped structure [8,9]. This enhancement can only be consistently described in a frame that treats, on an equal footing, the interaction of both Coulomb centers, projectile and residual target ion, upon the emitted electron.

In this paper we present measurements of electron spectra for ionization of a He target by H^+ projectiles with impact energies of 100 and 200 keV. We have chosen He as the target due to its simple atomic structure. For these energies single ionization dominates the electron emission from He [10]. In order to obtain a detailed view of the low-energy electron distribution, the electron energy E_e range extends from 1 up to only 16 eV. The present measurements complement previous results, obtained at higher electron energies [9]. The spectra were taken at fixed emission angles θ, covering the full angular range from $\theta=0°$ to 180°.

The data were obtained with our coaxial cylindric spectrometer, described elsewhere [9,11]. The procedure used in these measurements was the following: The target was provided by a gas stream emerging from a hypodermic needle. The distance d_{NB} between the needle tip and the ion beam was selected by taking a set of "background spectra" (target gas out) at $\theta=0°$, in such a way that, at the nearest working distance of $d_{NB}\cong 0.3$ mm (where $d_{NB}=0$ is the position where a sharp increase of background is observed) the counts per channel were the same as those obtained at large separations. In this way we avoid secondary electron emission from the needle tip and reach optimum conditions of target localization and consequently high "gas efficiency" [4] in the collision volume, localized at the object focus of the spectrometer.

The electron spectra for each emission angle θ were obtained by adding several runs for equal positive and negative θ. The spectra were then normalized to a full-range angular spectrum, taken at a fixed energy $E_e=15$ eV. With this procedure we corrected for changes in electron count rates, due to changing focusing conditions of the ion beam and the effective thickness of the concentrated gas target [4,9].

For the same angles, we also measured a set of energy spectra with a uniform, homogeneous distribution of the target, provided by a gas entrance into the collision chamber disposed sideways, far from the object focus of the spectrometer. The working pressure in the chamber, 6×10^{-6} Torr, was the same as with the atomic beam target. Then these spectra were again normalized to an angular spectrum, also taken with the uniform target. Our final results were obtained subtracting the spectra measured with the homogeneous gas target, considered as background, from those obtained with the atomic beam target.

For 100-keV H^+ projectiles and an emission angle $\theta=30°$, we also performed some test measurements to check the experimental conditions. First we observed that, for energies $E_e>3$ eV, the background counts without gas target, i.e., at a base pressure of $p=2\times10^{-7}$ Torr, were less than 1% of the "atomic beam target in" counts ($p=6\times10^{-6}$ Torr). With decreasing E_e, down to 0.5 eV, they went up to 10%. For the atomic beam target and θ equal to 30°, the shape of the spectra did not vary within statistical fluctuations when the working pressure was changed from 8×10^{-7} to 4×10^{-5} Torr. Additionally, we observed that the electron yield followed a linear behavior with pressure within that range. Moreover, the shape of the measured electron distributions did not change when the needle tip (of the gas source) approached 0.2 mm or removed up to 0.5-mm distance from to the edge of the ion beam. Another test consisted in moving the axial diaphragm O_1 (0.5-mm diameter) localized at the image focus of the spectrometer (see Figs in Refs. [9] and [11]) by ±0.5 mm from its optimum position. This, for the angular resolution used ($\theta_0=2°$), had no influence on the measured spectra within statistical uncertainties. Finally, the shape of our spectra was also insensitive to changes of the spectrometer angular acceptance from $\theta_0=0.5-2°$. We conclude from these tests that the information extracted from our spectra does not depend critically on the geometrical adjustments of the spectrometer, that may be subject to changes within their limits of reproducibility.

In Figs. 1 and 2, we show the experimental results for 100 and 200 keV, respectively. The normalization to absolute values of the cross section $d^2\sigma/dE_e d\Omega$ was carried out by obtaining the best agreement with our previous measurements of the doubly differential cross section for 100-keV H^+ on He [9]. Differences remained within

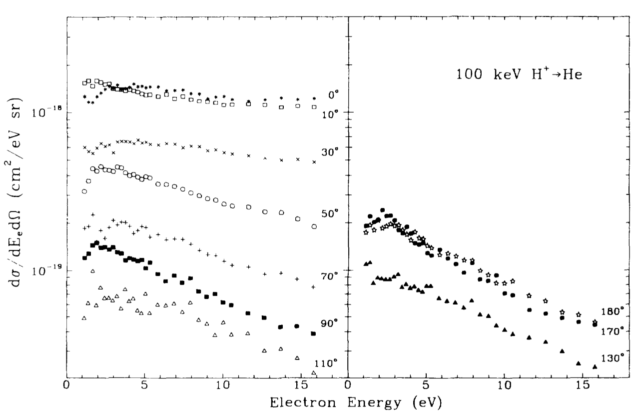

FIG. 1. Doubly differential cross sections for electron emission, at fixed angles θ, for 100-keV H^+ incident on He.

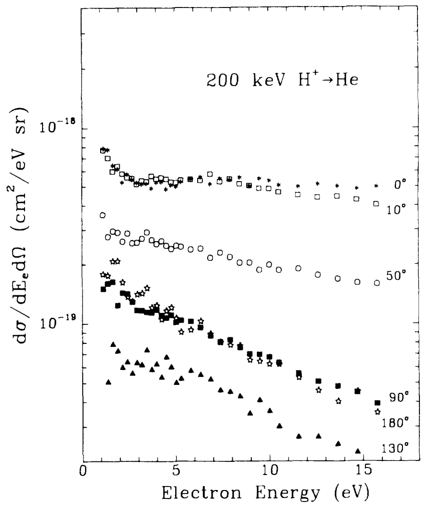

FIG. 2. Same as Fig. 1 for 200-keV H^+.

10% for $E_e\geq5$ eV and $0°\leq\theta\leq90°$, where the measured energy and angular ranges of both sets of data overlap. Our previous data [9] were normalized to absolute cross sections by integration of the doubly differential electron distributions, and then matching the integrals to the recommended total cross sections given by Rudd *et al.* [12]. Hence the present results are subject, on an absolute scale, to the uncertainties specified for the total cross sections in this reference [12]. Data for 200-keV H^+ were normalized relative to our 100-keV data.

We could assign an uncertainty of the spectra, measured for a given emission angle θ as a function of the electron energy E_e, of less than 10% for $E_e\geq3$ eV, and up to 30% for $E_e\approx1$ eV. These error limits were estimated from repeated runs performed at positive and negative angles $\pm\theta$. On the other hand, the estimated uncertainties in the relative normalization of the spectra taken at different emission angles θ were the following: For 100-keV projectile energy, 5% for $\theta=0°$, 10°, 30°, and 50°; 10% for $\theta=70°$, 170°, and 180°; and 20% for $\theta=90°$, 110°, and 130°. For the case of 200 keV, they were 5% for $\theta=0°$ and 10°; 10% for $\theta=50°$, and 25% for $\theta=90°$, 130°, and 180°.

We observe in Figs. 1 and 2 that, down to the lowest electron energies, there is a strong dependence of the cross section on the emission angle. It is clearly seen that a remarkable asymmetry of the soft-electron emission, very similar to that previously reported for a Ne target [4], is also present in the H^++He system. We remark that an analysis of existing data obtained at higher ion impact energies (1 MeV/amu) in other laboratories for ion-He systems [5] already indicates the existence of a forward-backward asymmetry, however small, in the low-energy electron emission.

We have attributed [3,4] this strong forward-backward asymmetry of the cross section for emission of low-energy electrons, centered at the residual target ion, to their Coulomb interaction with the receding projectile ions. We remark again that an analogous interpretation in this way had been accepted for a long time, to explain the asymmetry of the electron capture into the continuum (ECC) peak, for which the low-energy continuum electron states, centered at the projectile, are distorted by the potential of the residual target ion [7].

In Fig. 2 we observe that the forward-backward asymmetry decreases for 200-keV protons, mainly due to a strong decrease of the cross section for forward emission angles. This behavior can be attributed to a decreasing influence of the attraction of the low-energy electrons by the projectile which is receding with a greater speed. In other words, for weak collisions leading to soft-electron emission, "two-center effects" are becoming less important at larger impact energies, whereas for the ECC process which requires a violent interaction of the transferred electron with both Coulomb centers, the asymmetry of the ECC peak subsists.

In Figs. 1 and 2 it is shown that, as a function of θ, the cross section passes through a minimum in the angular range between 110° and 130°, and then approximately doubles its value, increasing to a maximum at 180°. An analogous behavior has been observed for the Ne target [4].

At this point we note that the measurement of electron emission in these two regions, SEE and ECC, presents different problems. For the soft-electron emission the reduced electron signal $Q(E_e)/E_e$ produces results proportional to the cross section $d^2\sigma/dE_e d\Omega$. Conversely, the swift increase, divergent in fact, of the cross section for ECC close to the projectile velocity, swept over by the resolution volume of the spectrometer, prevents access to that physical magnitude through the measured signal $Q(E_e)$. On the other hand, while electrons with energies near to that of the ECC peak are easily detected in measurements, there are severe difficulties in obtaining accurate measurements of low-energy electrons.

Recently it has been shown that the structure of the ECC peak can be discussed in the projectile reference frame [13], in the energy range from about 0.14 to 1.6 eV, by excluding the region close to the origin ($\mathbf{v}=\mathbf{v}_p$), affected by the above-mentioned strong instrumental distortions. In an analogous picture, we see then that our measurements only marginally include the above-mentioned energy range, now defined in the reference frame of the laboratory, but still can be used to obtain information about the structure of the emission of soft electrons. We remark that when we consider increasing electron energies away from the origin, it can be seen from Figs. 1 and 2 that the cross section continues to show a strong angular dependence. However, then it must mainly be attributed to the presence of the ridge-shaped enhancement that extends between the soft-electron and ECC peaks [8,9].

Measurements performed with He^{2+} projectiles, with the aim of studying the effect of increasing projectile charge, were rejected in view of poor statistics in the spectra at lower E_e, resulting after application of the subtraction procedure. They provided no further conclusions than those presented in previous measurements down to 5 eV [9].

In order to discuss the contribution to the measured signal from the superimposed uniform target distribution, we show in Fig. 3 the ratios between the spectra taken with the uniformly distributed target and those obtained with the atomic beam target, represented as a percentage. As one observes that these ratios depend strongly on energy and angle, it is evident that the shape and yield of the spectra resulting from the uniform target distribution vary with the emission angle θ in a different manner than those obtained with the atomic beam target.

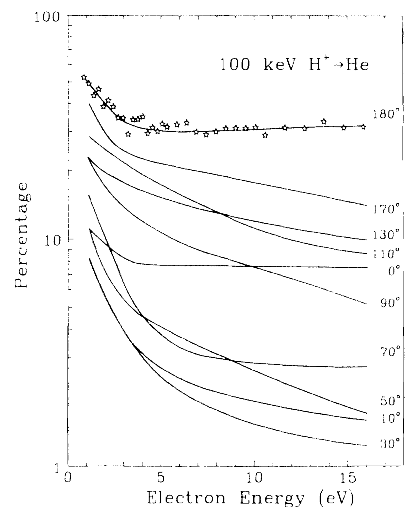

FIG. 3. Ratios of doubly differential electron distributions for a "uniformly distributed target" to an "atomic beam target," expressed as percentage. Full lines represent the interpolated values; for $\theta=180°$ the measured values only are also shown.

On the one hand, there is a geometrical effect due to the uniform target distribution that enhances the signal for θ close to 0° and 180° [11,14]. It is clear that when we subtract the signal obtained with the uniform target from that of the localized target, these undesired electrons are effectively eliminated. On the other hand, we reported [4] an additional distortion of the low-energy electron spectra, observed when an extended target is present. We proposed the possibility that the measured signal contains contributions of electrons, emitted along the projectile beam path, that can be detected within the spectrometer acceptance cone after a collision with a target atom (Fig. 4 of Ref. [4]). When we subtract the signal due to the uniform target distribution from that of the atomic beam target, the contribution from such undesired electrons is in large scale eliminated.

It is notable that the signal arising from the uniformly distributed target increases mainly for large emission angles, with the consequence that, after the subtraction, the cross sections are significantly smaller than those obtained if no subtraction were considered. Even so, as we have seen in Figs. 1 and 2, a cross-section enhancement at large emission angles is observed.

In summary, we have measured doubly differential low-energy electron emission from a He target induced by 100- and 200-keV protons. We observe a strong forward-to-backward asymmetry which becomes smaller for the higher projectile energy. A minimum in the angular distribution around $\theta = 120°$ is seen. We have shown that the extended gas target (6×10^{-6} Torr), superimposed on a highly localized atomic beam, gives rise to a correction, the subtraction of which is particularly important at very low electron energies and large emission angles. We maintain that this correction is necessary for the obtainment of reliable doubly differential cross-section data for low-energy electron emission.

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