Double Scattering Effects in the Ionization Spectrum Produced by Single Energetic Atomic Collisions

S. Suárez,* R. O. Barrachina, and W. Meckbach
Centro Atómico Bariloche and Instituto Balseiro,[†] *8400 S. C. de Bariloche, Río Negro, Argentina*

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We present experimental evidence of double scattering processes in the ionization of hydrogenic projectiles by single collisions with He targets at intermediate energies. We observe a distinctive shoulder in the electron velocity distribution in the forward direction at a velocity approximately 3 times greater than the velocity of the projectile. We interpret this structure as due to the emission of projectile electrons which have undergone two consecutive binary scattering processes: one with the target in first place, followed by a second one with the projectile nucleus. [S0031-9007(96)00587-X]

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The velocity distribution of electrons emitted in energetic atomic collisions has been actively investigated during the past three decades (see, for instance, the review paper by Rudd *et al.* [1]). This continuing interest has been prompted by information on the interactions and mechanisms involved in the ionization process which underlie these structures. The traditional picture contains three main features of the ionization cross section $d\sigma/d^3\mathbf{v}_e$. They are the binary encounter (BE) sphere [2] which can be produced by target or projectile ionization, and two sharp peaks which may appear, one centered in velocity space at the origin [3] and the other at the velocity $\mathbf{v}_p$ of the incident projectile [4–7]. These structures are closely related to two-body interactions of the ejected electron with the target and the projectile. In any case, the cusp-shaped peaks have been traditionally attributed to a mechanism where the ejected electron ends up in a low lying continuum state of the "charged" residual target or projectile. On the other hand, the binary encounter process occurs as the result of an impulsive two-body interaction when an electron initially bound to one atom (target or projectile) is expelled by an elastic binary encounter with the other atom (projectile or target). This process gives rise to a peak in the velocity distribution located on a "sphere" of radius approximately equal to v_p and centered either about $\mathbf{v}_e = \mathbf{v}_p$ or $\mathbf{v}_e = 0$, depending on whether the electron is originally attached to the target or the projectile, respectively. The velocity distribution of this initial bound state determines the shape of the shoulder in the ionization cross section $d\sigma/d^3\mathbf{v}_e$.

In due time, it became clear that the cusp-shaped peaks could not be properly described in terms of a simple two-body interaction mechanism of the electron with either the target or the projectile, respectively. Thus the prominent asymmetry of the peak at $\mathbf{v}_e = \mathbf{v}_p$ in isolated ion-atom collisions was interpreted as being due to the interaction of the electron with the residual target ion [8]. This effect showed the importance of thinking of the final continuum state as a three-body, not a two-body, system and led to an active search for other three-body effects. Experimental evidence of such an effect was given by the observation of an enhanced emission at speeds in between the target and projectile velocities [9]. Even though this first "ridge" was magnified by a finite-length target distortion [10], its existence has been considered to be the fingerprint of a three-body effect. A proper theoretical description of the ridge structure and cusp asymmetry is, however, a much tougher endeavour, in view of the fact that it requires the analysis of the electron moving in the combined potential fields of both atoms simultaneously (see, for instance, Ref. [11]).

Three-body effects do not represent a new idea in atomic collisions. For instance, their importance in electron capture collisions at high impact energies was already suggested by Thomas [12] in 1927. In a classical description, Thomas supposed that, in order to be captured, an electron has to emerge with a velocity close to that of the projectile. This implies a mechanism where the electron is knocked by the projectile towards the target nucleus at an angle of 60° with a speed $v_e \approx v_p$ where it undergoes a second elastic collision which deviates it back into the direction of the projectile. The momentum transfer to the electron in the first collision modifies the trajectory of the projectile which ends up moving in a direction $\theta_T \approx \sqrt{3}\, m_e/2M_p$, where m_e and M_p are the masses of the electron and the projectile, respectively. The search for a fingerprint of this double scattering mechanism [13] ended when the existence of a "Thomas" peak at θ_T in the angular differential cross section for the scattering of the projectile in a charge-exchange collision was experimentally confirmed by Pedersen, Cocke, and Stöckli [14] for the $\mathrm{H}^+ + \mathrm{He}$ system.

We investigate an ionization process in atomic collisions, looking for evidence of a three-body effect which resembles the double scattering mechanism of Thomas, but with no restriction on the scattering angle in either of the elastic collisions. Presently, we are considering an ionization mechanism where the electron suffers two binary collisions, one with each collision partner participating in the scattering process. Stretching this idea, it is possible to

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imagine a multiple scattering sequence where the electron suffers a series of binary collisions alternating between the target and the projectile. When restricted to the forward direction, this mechanism has some similarity to a classical model proposed by Fermi [15] for describing the acceleration of cosmic rays by collisions against moving magnetic fields. This model has been recently considered [16–18] within the context of speculations on cluster-impact fusion, where deuterons bouncing between a titanium deuteride surface and heavy-water cluster projectiles could buildup a high-energy tail of the D distribution [19].

A search for Fermi acceleration effects in atomic collisions has occurred in recent years. The first theoretical evidence of such an effect came from a quantum model with zero-range potentials in one and three dimensions, which featured peaks and dips located at velocities $v_e \approx 2^n v_p$ $(n = 1, 2, \ldots)$ in the forward $(\theta_e = 0°)$ and backward $(\theta_e = 180°)$ ionization spectra [20]. On the other hand, the experimental evidence for the presence of such structures has been ambiguous. While preliminary experiments on H_n^+ $(n = 1\text{–}3)$ traversing thin carbon foils failed to reveal any indication of enhanced electron emission beyond the binary encounter peak [21], a strong target dependence of the emission spectra at large electron energies for H^+ colliding with He, Ne, C, and Au has been tentatively attributed to a Fermi acceleration mechanism [22,23]. A similar multiple collision sequence has also been proposed with relation to the high-energy tails observed in the electron spectra induced by slow heavy ion bombardment of metals [24,25].

In Fig. 1 we show a scheme of what is to be expected on classical grounds from a sequence of binary collisions for the case of (a) projectile or (b) target ionization. This scheme generalizes the idea of knock-on collision sequences, showing how this three-body effect can modify the emission of electrons in directions out of 0° or 180°. In Fig. 1(a) a projectile electron suffers a binary collision with the target and acquires in the target frame a velocity approximately equal to v_p, with no restriction on the emission angle ϕ. As seen from the projectile, this electron obeys a $2v_p \cos\theta$ law, where the angle $\theta = (\phi - \pi)/2$ is defined in the moving system. If, prior to ejection, this electron is elastically scattered by the projectile, simple kinematical considerations show that its final velocity $\mathbf{v}_e$ would be located in velocity space on the surface of a sphere centered at $\mathbf{v}_p$ with radius approximately equal to $2v_p \cos\theta$. In principle, the accumulation of all these double scattering processes, corresponding to different values of the angle ϕ, would "fill" a sphere of maximum radius approximately equal to $2v_p$ around $\mathbf{v}_p$, giving rise to a shoulder in the velocity distribution, which in the forward direction is located at $v_e \approx 3v_p$. This same scheme can be repeated in order to consider the effect of a sequence of an arbitrary number of alternate binary collisions with the target and the projectile. It can also be applied *mutatis mutandis* to the case of target ionization, as it is shown in Fig. 1(b), where a double scattering process of the electron first with the projectile and then with the residual target would give rise to some structure in the velocity distribution for v_e up to $2v_p$.

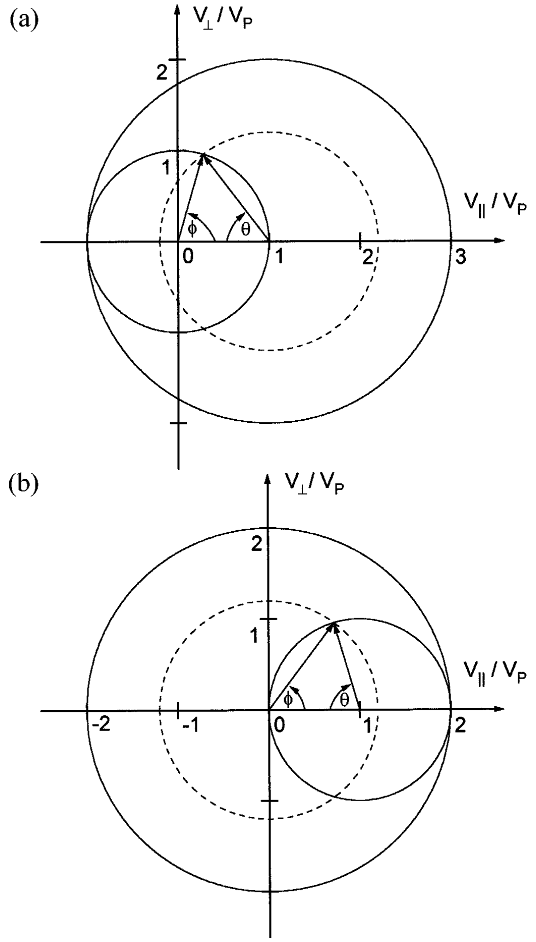

FIG. 1. Generation of a "secondary" binary shoulder by a sequence of two consecutive elastic collisions of a projectile (a) or target (b) electron with its collision partners. See the text for details.

In this paper we search for experimental evidence of these double scattering structures in ionization collisions of He by H^0 and H^+ impact. The experimental setup used, including our coaxial cylindrical electron spectrometer, is described in detail in a previous paper [26]. Briefly, a proton beam with energies ranging from 20 to 100 keV delivered by the Bariloche Cockcroft-Walton accelerator was partially neutralized to obtain a H^0 beam. Beam intensities were of the order of 1×10^9 particles/s. A collimator of 0.6 mm diameter allows the beam to enter the collision chamber and collide with a He target jet provided by a hypodermic needle. The needle tip, positioned at the spectrometer focus just above the beam line, permits us to obtain a localized target, thus reducing deformation of the measured spectra to a minimum and obtaining relatively large counting rates at small pressures in the scattering chamber. The He gas pressure in the chamber was approximately equal to 2×10^{-5} Torr, and linearity of counts with pressure was verified up to 5×10^{-5} Torr. An angular electron acceptance cone with a half angle $\theta_0 = 2.5°$ was used. The background without gas target at a pressure $P < 2 \times 10^{-7}$ Torr was measured and found to be smaller than 5% of the "target-in" signal, even within the highest energy range.

As count rates in the covered high-energy range were low, we increased the size of the orifice (O_1 of Fig. 1 in Ref. [26]) situated at the image focus on the axis of the two concentric cylinders of the spectrometer. This changed the electron energy resolution from 1% to 4%. No dependence of the shape of the measured spectra with the energy resolution was verified. The contribution of undesired low-energy electrons which could have been detected after hitting internal surfaces of the spectrometer was also tested by changing the preacceleration voltage at the entrance of the channeltron cone from +100 to −10 V. No changes were observed within the higher energy range of the detected electrons. Furthermore, when closing the orifice O_1 completely, the measured signal was found to be negligible.

It is clear from Fig. 1(b) that, for the $H^+ + He$ collision, no distinctive structure is expected to be observed in the electronic signal at $v_e \approx 3v_p$. Therefore, this signal can be employed to normalize the data corresponding to the $H^0 + He$ collision and thus enhance the double scattering shoulder. Characteristic double differential electron spectra are shown in Fig. 2, as resulting from 30 keV $H^0 + He$ and $H^+ + He$ collisions.

In Fig. 3 we show the ratio of the electron emission spectra in the forward direction $\theta_e = 0$ from H^0 and H^+ impact on He. For 20, 30, and 50 keV we observe a distinctive structure at $v_e \approx 3v_p$, which we interpret as due to the emission of projectile electrons that, in the same collision process, has undergone two consecutive binary interactions: one with the target in first place and one with the projectile nucleus.

For 20 keV the ratio tends to a constant value at large electron velocities, between $3.5v_p$ and $4.5v_p$; a region where no prominent features are expected either for the $H^0 + He$ (projectile ionization) or for the $H^+ + He$ (target ionization) process. Such a saturation was not observed in the 30 and 50 keV data due to the low count rates at higher electron velocities. However, it can be inferred from the high velocity dependence. Measurements performed at 67 and 100 keV showed poor statistics. This was due mainly to a decrease with increasing projectile energy of the intensity of the H^0 beam by charge exchange [27]. At this higher energy range, no structure at $v_e \approx 3v_p$ could be identified within the large experimental uncertainties. In view of these results, further studies of this effect for larger projectile velocities would be desirable in order to discern whether it is a low-energy effect or if it can be observed even for high energies. In this case a comparison with a two-center

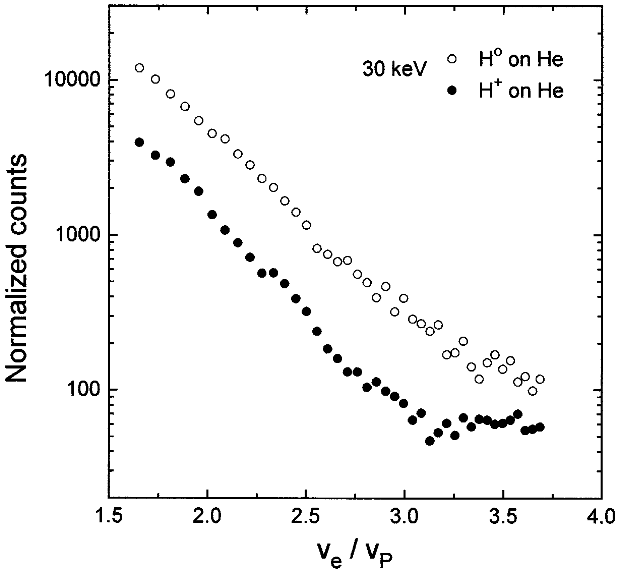

FIG. 2. Double differential electron distributions in the forward direction resulting from 30 keV $H^0 + He$ (○) and $H^+ + He$ (●) ionization collisions.

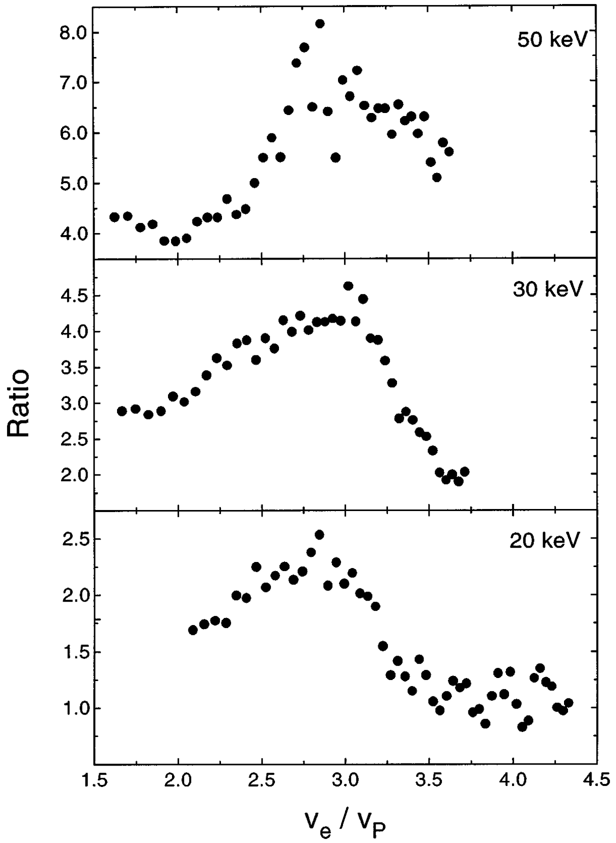

FIG. 3. Experimental ratio between the electronic intensities in the forward direction for $H^0 + He$ and $H^+ + He$ collisions at 20, 30, and 50 keV.

theory [28], valid for these energies, would be possible and could give rise to a better understanding of the effect.

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*Also member of the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.

†Comisió Nacional de Energía Atómica y Universidad Nacional de Cuyo, Argentina.

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