Double-Differential Distributions Produced by Collisional Electron Loss into the Continuum for the H^0-He System

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Detailed double-differential distributions in energy and angle of emission of electrons ejected into the continuum by collisional ionization of H^0 projectiles with He are measured. Anisotropies of the resulting three-dimensional cusps are discussed in terms of contour lines taken at different levels. They show a structure that calls for an inclusion of higher terms in the expansion of the cross section, not contained in first Born calculations of Day and of Briggs and Day.

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It is the purpose of the present work to measure and discuss double-differential distributions of electrons resulting from collisional ionization of energetic projectiles that bring bound electrons into a collision with a target atom. The simplest possible projectile containing one electron, H^0, was chosen; the target was He. The main contribution to this electron emission stems from weak collisions, that is collisions of low momentum transfer.

In a reference frame moving with the projectile of velocity $\vec{v}_i$, electrons of low speed $v' \ll v_i$ are subject to the Coulomb attraction by the residual projectile ion. In the context of "electron transfer to the continuum (ETC)" this process of projectile ionization is known as "electron loss to the continuum (ELC)." The other possible ETC process, "electron capture to the continuum (ECC)," implies a real transfer of an electron from a target bound state into a low-lying continuum state of an ionic projectile. We deal in the laboratory frame with electrons of velocities $\vec{v} \approx \vec{v}_i$, that is speeds close to v_i and small emission angles θ defined with reference to the direction of the ion beam. These electrons are measured with relative ease.

Theoretical discussions of both ETC processes lead to a cross section which diverges when $\vec{v} \to \vec{v}_i$; $v' \to 0$ and can be written as[1]

$$\frac{d\sigma}{d\vec{v}} = \frac{d\sigma}{d\vec{v}'} = \frac{1}{|\vec{v}'|} F(\vec{v}'; v_i) = \frac{1}{v'} F(v', \cos\theta'; v_i). \tag{1}$$

Here θ' is the polar angle of $\vec{v}'$, defined in the moving frame and measured with respect to the direction of $\vec{v}_i$.

Early theoretical discussions of ECC[2] and subsequently also of ELC[3] led to $F(v', \cos\theta; v_i) = F(v_i)$, that is to a cross section whose shape is only determined by the divergent factor $1/v'$. Deviations from this simple spherically symmetrical shape, in the sense of asymmetries and anisotropic structure, are introduced through a dependence of F on v' and θ'. An expansion of the transition probability of ETC processes, introduced by Garibotti,[4] serves to put such deviations into evidence. It leads to

$$\frac{d\sigma}{d\vec{v}'} = \frac{1}{v'} \left[\sum_{n,j} B_j^{(n)}(v_i) v'^n P_j(\cos\theta') \right]. \tag{2}$$

Most of the experiments on ETC to date have been performed by measuring energy or velocity distributions of electrons emitted in the direction of the ion beam. As a result of convolution of $d\sigma/d\vec{v}$ with the acceptance in angle and energy or speed of an electron spectrometer used for measurement, which can be characterized by a cylindrical resolution volume defined in $\vec{v}$ space,[4] sharp cusp-shaped peaks, as measured for the first time by Crooks and Rudd,[5] are obtained. For the case of ECC such "longitudinal" electron spectra exhibit a strong asymmetry in the sense of an enhancement of the emission of lower-energy electrons. This has been observed with heavy[6] and light[4,7] projectiles and has been discussed in Ref. 4 by maintaining terms up to $n = 1$ and $j = 1$ in Eq. (2). The term

$$(B_1^{(0)}/v')P_1(\cos\theta') = (B_1^{(0)}/v')\cos\theta' \quad (B_1^{(0)} < 0)$$

mainly accounts for the appearance of these negatively skewed cusps and has been used as an indicator[8] of the contributions of second-order Born terms[9] to $d\sigma/d\vec{v}$. Higher terms in Eq. (2) also result from a multiple-scattering approach of Garibotti and Miraglia.[10]

Measurements performed with heavy ions revealed that the negative cusp skewness disappears when ELC becomes predominant.[6] For ELC, the target atom plays the role of an ionizing projectile in the moving frame of reference, and a weak collisional interaction is sufficient to emit electrons into low-lying projectile continuum states. Consequently a first Born-perturbation treatment was considered suitable by Day[11] and Briggs and Day[12] to describe details of the resulting electron distribution. This first-Born calculation does not lead to diverging asymmetric terms in the cross section [Eq. (2)], that is terms with $n=0$ and odd j; however, terms with $n=0$ and even j may appear. The cited discussion is limited to the inclusion of only two terms, characterized by $n=0$, $j=0$ and 2; that is

$$\frac{d\sigma}{d\vec{v}} = \frac{1}{v'}\left[B_0^{(0)} + B_2^{(0)} P_2(\cos\theta')\right] = \frac{A}{v'}\left[1+\beta P_2(\cos\theta')\right] = \frac{A}{v'}\left[1-\frac{\beta}{2}+\frac{3\beta}{2}\cos^2\theta'\right]. \quad (3)$$

We considered that a most sensible and direct test for anisotropies would be obtained from contour lines represented in polar coordinates as a function of v' and θ', obtained from three-dimensional cusps measured as a function of electron energy or speed and angle of emission.

In Figs. 1(a) and 1(b) we show contour lines of $d\sigma/d\vec{v}$ as they result from Eq. (3) for $-1 \leq \beta \leq 0$ and $0 \leq \beta \leq +2$. At different chosen levels these contour lines repeat themselves in shape, but not in size. However, because of the remarkable influence that results from convolution with the instrumental resolution volume, these contour lines suffer deformations which depend on their level and are strongest close to the peak top. In Fig. 2 we show such contour lines as obtained from convolution with our experimental resolutions (see below) for $\beta=-1$, $+0.15$, and $+1$. It is noteworthy that for $\beta=+1$ two separate peaks are distinguished. They correspond to two almost symmetric maxima, as predicted by Day[11] for longitudinal spectra when $\beta>+0.5$. These look like the cusp inversion discussed recently by Burgdorfer[13] for the case of incident $2p_0$ projectiles.

Proton beams of 105-keV energy, delivered by the Bariloche Cockcroft-Walton accelerator, were neutralized in part by electron capture in a differentially pumped He-gas cell. The emerging protons were electrostatically deflected out of the beam; the H^0 beam entered our coaxial cylindric electron spectrometer.[4] The target consisted of an atomic He beam emerging from the 0.25-mm bore of a hypodermic needle. The Faraday cup used as a monitor of collected beam particles was provided with a thin foil through which the entering H^0 beam was charge equilibrated[14]; the ensuing proton fraction was measured. A half-angle of the electron acceptance cone into the spectrometer of $\theta_0 = 0.5° = 0.87\times10^{-2}$ rad was chosen. The relative resolution in electron energy E_e or speed v_e was

$$R = (\Delta E_e)_{\rm HWHM}/2E_e = (\Delta v)_{\rm HWHM}/v = 0.08\times10^{-2}$$

(HWHM denotes half width at half maximum). θ_0

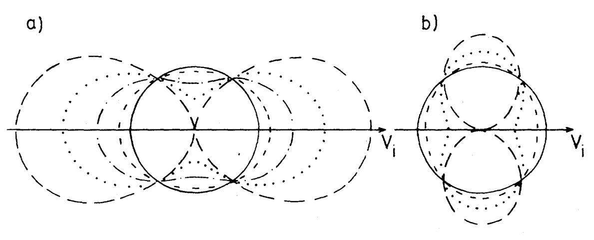

FIG. 1. Contour lines of $d\sigma/d\vec{v}$ given by Eq. (3) for different values of β: (a) solid curve, $\beta=0$; short-dashed curve, $\beta=+0.15$; dot-dashed curve, $\beta=+0.5$; dotted curve, $\beta=+1$; long-dashed curve, $\beta=+2$; (b) solid curve, $\beta=0$; short-dashed curve, $\beta=-0.15$; dotted curve, $\beta=-0.5$; long-dashed curve, $\beta=-1$.

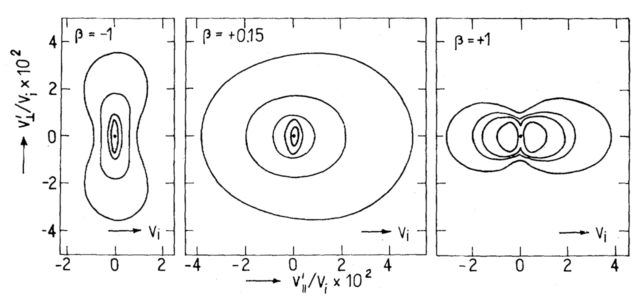

FIG. 2. Contour lines for different β, obtained from convolution of $d\sigma/d\vec{v}$ [Eq. (3)] with $\theta_0=0.5°$, $R/\theta_0=0.09$. Levels, referred to 1 at origin, are, for $\beta=-1$, (dot) 1, (curves) 0.75, 0.5, 0.25, 0.125; for $\beta=+0.15$, (dot) 1, (curves) 0.9, 0.75, 0.5, 0.25, 0.125; for $\beta=+1$, (dot) 1, (curves) 1.2, 0.9, 0.75, 0.5. Scales represent longitudinal and transverse components of $\vec{v}'/v_i$, multiplied by 10^2.

and R determine a "resolution volume" in $\vec{v}_e$ space,[4] given by a flat cylinder of diameter $2\theta_0 v$ and height $2Rv$ ($R/\theta_0 = 0.09$).

Electron spectra measured at $\theta = 0$ confirmed the symmetry of "longitudinal" cusps, as it results from the first-Born treatment of Day[11] and Briggs and Day[12] [Eq. (3)]. This enabled us to compare measured anisotropies with those resulting from this theory. In order to obtain the desired three-dimensional cusps, we had to measure spectra at small angles ($\theta < 7°$), where most of the peak-to-tail transition of these cusps occurs. Because the angular acceptance of measured electrons is determined at their exit, our electron spectrometer permitted such measurements without intercepting the ion beam. This feature, already introduced in an earlier but different design by McGowan,[15] allows us to monitor the ion beam by collection in a Faraday cup at all angles, including small θ, and avoids the disturbing appearance of background electrons produced by ions hitting the face of the analyzer entrance apertures.[15]

Spectra at angles $\theta \neq 0$ were obtained by turning the inner cylinder (Fig. 2 of Ref. 4), together with the electron exit tube and detector mount, through an azimuthal angle β around the spectrometer axis. In this way the plane containing the path of the deflected and measured electrons was also turned around this axis. The angle θ resulted from the azimuth β as $\theta = 2\sin^{-1}(\sin\frac{1}{2}\beta \times \sin\alpha)$. Here $\alpha = 42.3$ is the angle at which the central ray of the measured electron beam cuts the spectrometer axis.

Figure 3 shows a three-dimensional ELC cusp that results from spectra obtained as a function of electron energy E_e at different angles θ. To our knowledge this is the first time such detailed experimental information about an ETC process has been presented. Menendez *et al.*[16] measured ELC distributions at different θ up to almost 180°. Their work, obtained with different projectiles including H^-, is not directly related to the present study.

Distributions like that shown in Fig. 3 permit the desired evaluation of anisotropy as a function of θ' and its comparison with theory by drawing contour lines obtained from the experimental three-dimensional cusps at prefixed fractional levels of the peak height, as shown in Fig. 4. A comparison with the theory of Day[11] and Briggs and Day[12] leads to the following conclusions:

Apparently the experimental contours are approximated best by the convoluted theoretical contour lines that result from Eq. (3) for $\beta \approx +0.15$. However, we are not yet able to make a quantitative statement about a value of β because care must be taken with respect to the experimental effective beam-gas interaction volume as a function of θ.

A quite noticeable difference between experiment and theory consists in that the experimental contour lines show a superposed anisotropic structure that is more complicated than any deformations which can be expected from Eq. (3). It is obvious that, beginning with a P_4 term, higher terms with even $j > 2$ must be introduced in

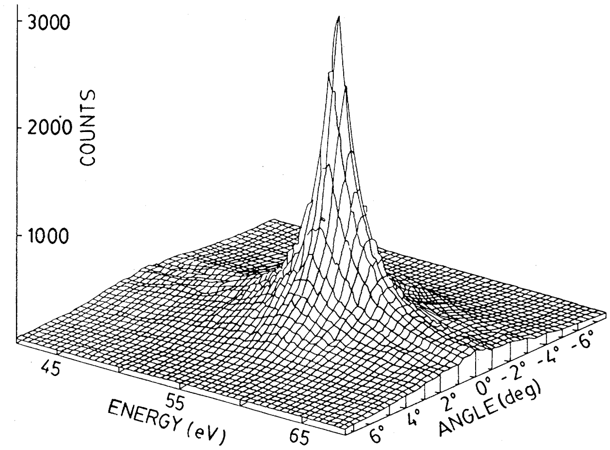

FIG. 3. Three-dimensional ELC cusp measured, as a function of electron energy E_e and emission angle θ, with 105-keV H^0 interacting with He.

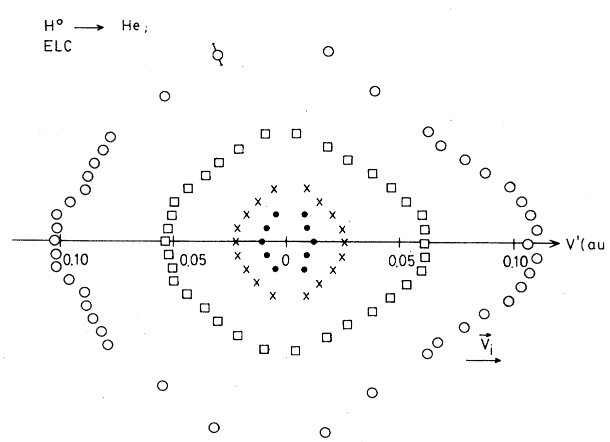

FIG. 4. Experimental contour lines obtained from the cusp of Fig. 3 and taken at the indicated fractional levels of the peak height.

the expansion of the cross section in order to account for this additional structure.

The present work represents a first step in the investigation of details of the emission of low-velocity electrons produced by collisional ionization in the frame of a moving projectile. Such studies also permit conclusions about the shape of double-differential distributions of very low-velocity electrons emitted from collisionally ionized atomic targets which are not easily accessible to direct measurements.

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