Effects of the Wannier Ridge on Secondary-Electron Spectra in Proton-Helium Collisions

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We present high-resolution electron spectra for electrons ejected in the forward direction by protons and neutral hydrogen in collisions with He gas. The spectra show the expected electron transfer to the continuum peak, but also show a 0° ridge extending to the lowest electron energies measured. We propose that this new secondary-electron component represents electrons which propagate on the saddle of the potential surface produced by the two positive ions H^+ and He^+ in the intermediate collision complex.

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The understanding of secondary-electron production in ion-atom collisions is based on selection of regions of the secondary-electron spectra where the full complexity of the three-body projectile-target-electron system is avoided and the production of electrons is regarded as an impulsive interaction with a simple two-body system. In this spirit, the standard Bethe[1] theory of ionization employs the Born approximation for the projectile-electron interaction and exact two-body electron-target continuum functions. Because the electrons are ejected impulsively from a target bound state into a target continuum state, this mechanism is often referred to as direct ionization. Twenty years ago it was realized that another component,[2] analogous to electron capture,[3–5] exists in which secondary-electron production takes place by electron transfer to continuum states of the projectile. This mechanism is now referred to as electron capture to the continuum, ECC. It is recognized, however, that these two well-known mechanisms represent only limiting cases of the full three-body final state in which all three particles —projectile P, target ion T, and electron e—interact equally. The purpose of this paper is to present secondary-electron velocity distributions that cannot be interpreted in terms of a dominant two-particle final state, but require equal interaction of the electron with both target and projectile ions in the intermediate and final states.

Our interpretation exhibits some suggestive similarities with the Wannier[6] theory of electron emission for the escape of two electrons from a positive ion core.[7,8] Here it is also necessary to treat the simultaneous interaction of three charged particles in the final state. To develop this analogy further, consider the potential surface of a charged projectile P and ionized target T separated by a distance of 2 a.u., shown in Fig. 1(a). Three features are prominent, namely the potential minima localized at P and T and the saddle point midway between P and T. It is well known that secondary-electron spectra exhibit sharp peaks in the electron velocity distribution at electron velocity $\mathbf{v}_e=\mathbf{v}_i$ corresponding to electrons traveling at the projectile[9] velocity $\mathbf{v}_i$ and at $v_e=0$ corresponding to electrons at rest with respect to T. Such a velocity distribution is shown schematically in Fig. 1(b). Notice that the two peaks in the electron spectra mirror the two minima in the potential surface. In this paper we will also show that there is a ridge in the secondary-electron spectra which is sharply focused in angle along the line joining P and T, but is smoothly distributed in velocity between $\mathbf{v}_e=\mathbf{v}_i$ and $v_e\approx 0$. Indeed, there is some evidence that this 0° ridge extends beyond $v_e=v_i$. The observed distribution appears to correspond to the saddle region of the potential surface between P and T; thus it corresponds to electrons which propagate in the combined fields of both P and T. This part of the secondary-electron distribution therefore reflects an intrinsic three-particle mechanism for electron ejection. The key point of this work is that this intrinsically three-particle part of the secondary-electron spectra is seen as an observable ridge at 0° in the secondary-electron spectra for electrons with velocities distributed between $v_e\approx 0$ and $\mathbf{v}_e=\mathbf{v}_i$ and even for $v_e > v_i$.

We have measured doubly differential electron dis-

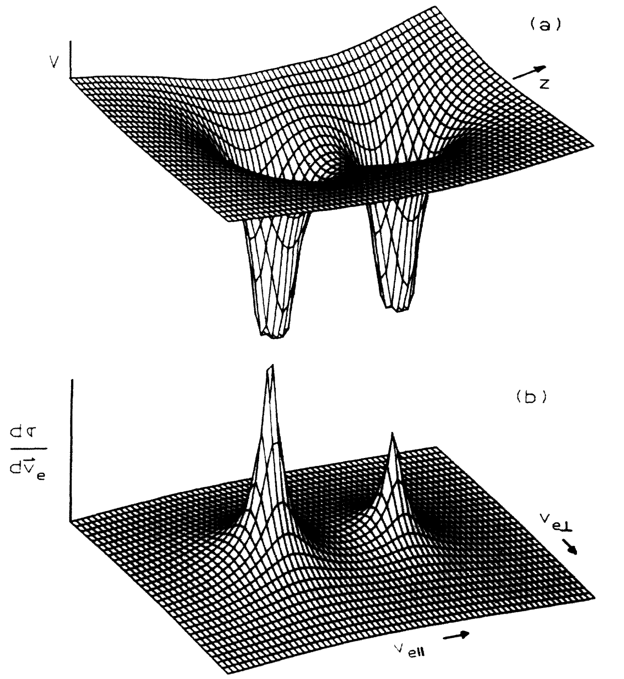

FIG. 1. (a) Potential surface due to two charged particles P and T with $Z_P = Z_T = 1$. The potential near the singularities at the two nuclei is truncated at $V = 5$ a.u. (b) Schematic plot of the velocity distribution of secondary electrons from $H^+ + H^0$ collisions showing the direct ionization peak at $v_e = 0$ and the ECC peak at $\mathbf{v}_e = \mathbf{v}_i$.

tributions for $H^+ + He \rightarrow H^+ + He^+ + e^-$ at 170 keV near the forward direction with high velocity and angular resolution (half widths of $R = \Delta v_e / v_e \approx 0.3\%$ and $\theta_0 \approx 1^0$) using an apparatus described earlier.[10-12] Following the analysis of Ref. 10 we extract the doubly differential velocity distribution shown on the right-hand side for 1.8 a.u. $< v_e <$ 4 a.u. in Fig. 2. In addition to the usual pronounced continuum capture peak there is a sharp ridge at $v_{e\perp} = 0$. The ridge extends from the lowest velocity measured to electron velocities greater than the matching velocity. The ridge has not been noted before but shows up clearly in the present data.

The $H^+ + He$ data in Fig. 2 correspond to electron velocities between 40 and 200 eV where the continuum capture peak is most prominent. To investigate the ridge in a region where direct ionization as described by the Bethe theory predominates we have measured the velocity distribution of secondary electrons in $H^0 + He$ collisions. This distribution shows the usual peak corresponding to direct ionization of H^0 at the matching velocity, $\mathbf{v}_e = \mathbf{v}_i$, where v_e is the electron velocity in the laboratory frame. A ridge also appears and to compare this ridge with the one for $H^+ + He$ we have plotted the $H^0 + He$ secondary-electron spectra on the left-hand side of Fig. 2. In this way the direct ionization cusp appears at $\mathbf{v}_e = \mathbf{v}_i$ on the left-hand side of Fig. 2. Notice that there is a ridge near

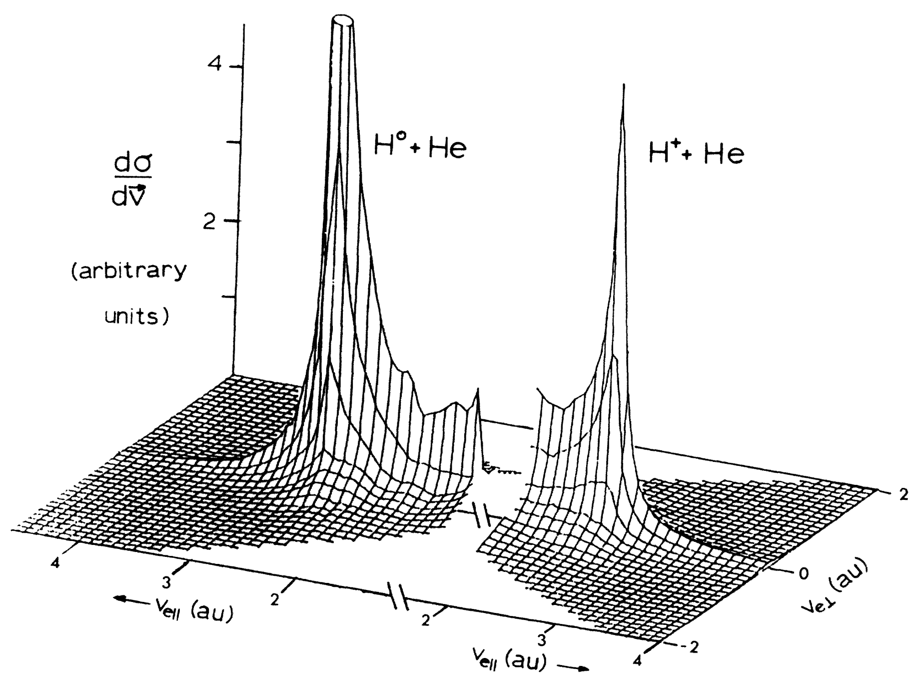

FIG. 2. Combined velocity distribution of electrons produced in $H^+ + He$ and $He + H^0$ collisions. The data for $H^+ + He$ collisions include the ECC peak while the data for $He + H^0$ collisions include the peak due to direct ionization of H^0 at $\mathbf{v}_e = \mathbf{v}_i$. In addition to the two peaks there is a ridge of secondary electrons concentrated at zero transverse electron velocity. The ordinate, labeled $(d\sigma/d\mathbf{v}_e)_{ex}$, is proportional to the measured signal divided by the resolution in velocity space, i.e., by $2\pi R\theta_0^2 v_e^2$, and is plotted on a linear scale in arbitrary units.

$v_{e\perp}=0$ throughout the velocity range investigated. The arbitrary unit of the cross-section scale for the H^0+He data differs from that for the H^++He data and is chosen so that the height of respective ridges are comparable.

The data in Fig. 2 show that a pronounced ridge near $v_{e\perp}=0$, sharply focused in angle but broadly distributed in energy, exists in secondary-electron spectra in H^++He collisions. This is reminiscent of "potential ridge" phenomena in the context of the Wannier[6] theory where slow electrons emitted in the photoabsorption of H^-, for example, are sharply focused in angle but smoothly distributed in energy.[13] Accordingly, we propose that the secondary-electron ridge observed here arises from electrons which propagate in the saddle-point region of the potential surface shown in Fig. 1(a).

To investigate this effect quantitatively, we have solved the time-dependent Schrödinger equation for H^++H collisions near the saddle point in an approximation where the potential is expanded in powers of the electron coordinate. As in the Wannier theory, only quadratic terms are retained. The resulting time-dependent one-electron Schrödinger equation

$$i\dot{\psi}(\mathbf{r},t)+[-\tfrac{1}{2}\nabla^2+V(\mathbf{r},t)]\psi(\mathbf{r},t)=0 \tag{1}$$

can then be solved exactly.[14] The solution has the form used in the Wannier theory for electron motion,[7]

$$\psi(\mathbf{r},t)=\exp[-S_0(t)-S_1(t)(x^2+y^2)-S_2(t)z^2]. \tag{2}$$

The differential equations for S_0, S_1, and S_2 can be solved exactly following the methods of Peterkopf[7] and Feagin,[13] the main difference being that the internuclear coordinate R is replaced by vt. If we assume that there is a component near the saddle at some time $t=t_0$ after the collision and if we take this component to be a Gaussian,

$$\psi(\mathbf{r},t_0)=\exp\{-[x^2+y^2]/d_\parallel^2-z^2/d_\perp^2\},$$

where $d_\parallel$ and $d_\perp$ are constants, then Eq. (2) gives $\psi(\mathbf{r},t)$ at later times and in particular in the limit $t\rightarrow\infty$.

The quantity of interest is the final velocity (or momentum) distribution. For the case of $vt_0=2$ a.u. and $v=2.61$ a.u. corresponding to 170-keV protons we find for the final velocity distribution

$$P(v_e)=\exp\{-0.5[0.375d_\parallel(v_{e\parallel}-v_i/2)]^2 -0.5[1.85d_\perp v_{e\perp}]^2\}. \tag{3}$$

This contrasts with the distribution $P_0(\mathbf{v}_3)$ which obtains in the absence of the final-state motion on the saddle:

$$P(\mathbf{v}_e)=\exp\{-0.5[d_\parallel v_{e\parallel}]^2-0.5[d_\perp v_{e\perp}]^2\}. \tag{4}$$

We see that the distribution narrows by a factor of 1.85 in the perpendicular direction and broadens by a factor of 2.7 in the parallel direction. The coefficients of $v_{e\parallel}$ and $v_{e\perp}$ are nearly independent of the initial conditions, and, since most wave functions can be written as superpositions of Gaussians, all initial velocity distributions will exhibit the narrowing in the perpendicular direction given by Eq. (3). This shows that the observed ridge in Fig. 2 can be explained as due to electron motion on the potential saddle which narrows the distribution in the perpendicular direction and broadens it in the parallel direction.

The theory applies strictly only to situations, such as the ionization of a neutral atom by a proton, where there are known to be two positively charged particles in the final state. In the case of H^0+He collisions there will still be a ridge component since approximately 50% of the collisions which ionize He also ionize H_0[15] and the theory applies in the commonly used independent-particle approximation.

It is noteworthy that a "ridge riding" or "Wannier" mechanism for ionization in H^++H collisions at lower velocities has been proposed on the basis of *ab initio* computer simulations of ionization.[16] This simulation finds a component of the electron wave function concentrated on the potential saddle at some time t_0 after the collision. We have shown that such components can give rise to a 0° ridge in the secondary-electron spectra. This component maximizes at an electron velocity corresponding to the velocity $v_i/2$ of the ridge. The broad peak in the parallel velocity distribution sits on top of a "background" distribution which comes mainly from direct ionization in the proton energy range employed here. Because the background part decreases rapidly with increasing electron energy, the broad peak may not actually appear as a noticeable structure in the parallel velocity distribution. Its main signature is the narrow peak in the perpendicular direction. Our observed spectra clearly show such a Wannier-type component and suggest that further measurements emphasizing the ridge feature could prove fruitful for the understanding of electron motion on potential saddles.

The presence of the potential saddle is a key element of our interpretation of the observed ridge spectra. The relevance of the saddle can be checked by observation of the electron distribution in H^-+He collisions. Except for the rare events in which H^- loses two electrons and He is simultaneously ionized, the potential saddle is absent in the final state of the system. In this case we do not expect a pronounced 0° ridge. There is still a potential saddle in the intermediate collision complex, but screening due to the four electrons of H^-+He should considerably reduce its effect. Of course, observations over a wider range of target species and incident velocities, particularly for those velocities discussed by Winter and Lin[16] are also indicated. Furthermore, in asymmetric systems the saddle point moves at a velocity given by $v_i/[1+(Z_P/Z_T)^{1/2}]$, where Z_P and Z_T are the charges of the projectile and target, respectively, in the final state. The secondary-electron spectra could then show some ridge structure in the vicinity of this particular velocity.

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