(e, 2e) Investigation of Atomic Hydrogen and Helium Close to Threshold

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Triple differential cross sections of the electron impact ionization of atomic hydrogen close to threshold have been measured. The angular correlation of the outgoing electrons have been determined at 4-eV excess energy and are compared with results obtained with helium. A method is proposed allowing one to measure the range of the threshold law. The data are analyzed using a partial-wave method. Although the asymptotic states of the two processes are the same—the charge of the ion is $Z=1$ in both cases—the triple differential cross sections are drastically different.

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The break-up of a hydrogen atom by electron impact leads to a three-body system with a proton and two free electrons. For all other targets additional electrons are involved and only at large distances does the ion appear to be a pointlike charge. Such a problem is extremely difficult to solve theoretically since all particles are charged and the Coulomb force allows for the exchange of energy, momentum, and angular momentum. Especially when the free kinetic energy of the system is small, the motion of the two escaping electrons is influenced by their mutual repulsion and therefore correlation effects are important.

The influence of the electron correlation on the threshold escape was considered for the first time in 1953 by Wannier,[1] who determined in a classical-trajectory calculation the energy dependence of the integrated ionization cross section to be $\sigma \sim E^{1.127}$. The fractional exponent is a consequence of correlation effects. In the mean time this threshold law has been proved experimentally not only for the integrated but also for the differential cross sections.[2]

The same energy dependence of the integrated cross section was derived by a quantum-mechanical treatment by Rau[3,4] and Peterkop,[5] but with the restriction that the total angular momentum in the final state is zero. These theories suggested that both the integrated and the differential cross sections would contain no information about the dynamics of the collision, except for the overall normalization factor.

After a first theoretical approach[6] including higher angular momentum states and after some experimental work,[7-9] further theoretical investigations have been made[10-12] on the escape of two electrons near threshold including higher total angular momentum. As a result of these theories [usually referred to as the Wannier-Peterkop-Rau (WPR) theory] it turned out that in addition to the $L=0$ state at least a few $\{LS\pi\}$ states (total angular momentum L, total spin S, and parity π with $L>0$ should be relevant even very close to threshold.

The simultaneous detection of both continuum electrons using coincidence techniques allows one to study correlation effects and gives evidence for the mixing of the different $\{LS\pi\}$ states involved in the process. Up to now the intensities and phase shifts of the different partial waves have not been determined by threshold theories. Therefore the present theoretical models do not calculate correlations of the outgoing electrons.

Selles, Huetz, and Mazeau[13] have measured triple differential cross sections of the electron impact ionization of helium for different excess energies from 4 eV down to 0.5 eV. Extending the WPR theory they were able to deduce analytical expressions for the partial-wave amplitudes for all relevant $\{LS\pi\}$ states with $L \leq 2$ describing explicitly the dependence on the excess energy E and on the kinematical conditions. By a fit of their data in the frame of the WPR theory the amplitudes of the different states with $L \leq 2$ relative to the $^1S^e$ state could be extracted.

The present measurements have been performed in a coplanar crossed-beam coincidence electron-impact spectrometer which has been described earlier.[14]

The angular dependencies have been analyzed in terms of partial waves as proposed by Altick and Rösel.[15] The method is based on general properties of the cross section and provides the determination of the maximum angular momentum L_{max} present in the final state.

Two experimental examples of the triple differential cross section of helium at 4-eV excess energy are shown in Fig. 1. In Fig. 1(a) the cross section is measured for equal detection energies $E_1=E_2=2$ eV as a function of the scattering angle ϑ_1. The angle Θ_{12} between both electrons is kept constant to $\Theta_{12}=180°$. Such a measurement allows us to examine the mixing of the different $\{LS\pi\}$ states. The measured cross section for helium (dots) shows a steep decrease with increasing ϑ_1, a minimum around $\vartheta_1=50°$, and a pronounced maximum at $\vartheta_1=90°$. The shape of the cross section is symmetric with respect to $\vartheta_1=90°$ as required by the Pauli principle, since both electrons are indistinguishable and therefore the interchange of the scattering angles should leave the cross section unchanged. The broken and the solid line in Fig. 1(a) are the results of a partial-wave analysis

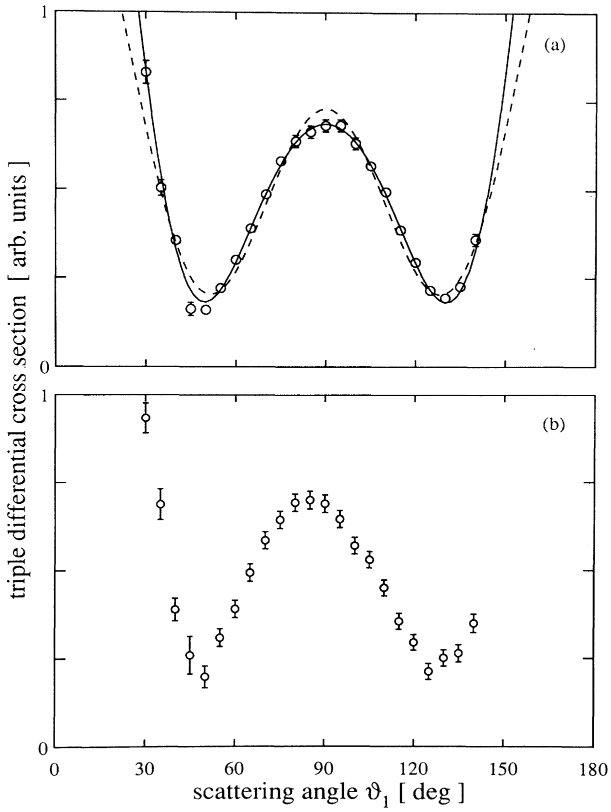

FIG. 1. Triple differential cross section for helium at 4-eV excess energy measured as a function of the scattering angle ϑ_1 while ϑ_2 is equal to $180° - \vartheta_1$. (a) Detection energies are $E_1 = E_2 = 2$ eV. ---, partial-wave fit including all states up to D wave; ——, partial-wave fit including all states up to F wave. (b) Detection energies are $E_1 = 3.5$ eV and $E_2 = 0.5$ eV.

where all states up to $L = 2$ and $L = 3$, respectively, have been included. The F wave must be taken into account in order to reproduce the measured angular distribution, since the quality of the fit improves considerably. A special least-squares fit has been employed to ensure a global minimum with respect to all fit coefficients. The consideration of a G wave in the fit gives no further improvement so that all states with $L \geq 4$ seem to be negligible. Also, calculations of angular dependences as a function of ϑ_1 with several constant difference angles Θ_{12} ($\Theta_{12} = 165°$, 150°, 135°, and 120°) have been performed. A distinct F-wave contribution is always found.

From the WPR theory it turns out that the wave function for the $^1S^e$ and $^3P^e$ states is symmetric with respect to radial interchange, whereas the $^3S^e$ and $^1P^e$ states are antisymmetric. All other states with $L \geq 1$ are constructed from a radial symmetric and a radial antisymmetric part. Radially symmetric states lead to a threshold law of the total ionization cross section, $\sigma \sim E^{1.127}$ with E being the excess energy, whereas the antisymmetric states give a different threshold law, namely $\sigma \sim E^{3.881}$. Within the threshold range the states with

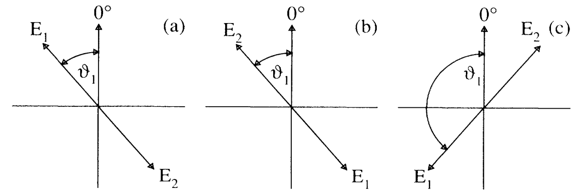

FIG. 2. For explanation see text.

the larger exponent are suppressed. Whether the cross section contains contributions from radial antisymmetric states can be tested in terms of the triple differential cross section. This requires the measurement of an angular dependency with the difference angle Θ_{12} fixed to $\Theta_{12} = 180°$ and an asymmetric sharing of the excess energy, e.g., $E_1 > E_2$ [see Fig. 2(a)]. The interchange of the detection energies [Fig. 2(b)] is equivalent to the exchange of $\vartheta_{1,2}$ by $180° - \vartheta_{1,2}$ [Fig. 2(c)]. It is obvious that the configurations in Figs. 2(b) and 2(c) are identical because of the symmetry with respect to the momentum of the incident electron which is supposed to come in along the 0° direction. When the excess energy is within the threshold range the cross section contains only radially symmetric states. In this case the cross sections measured in the configurations according to Figs. 2(a) and 2(b) must be equal because the radial interchange is asymptotically equivalent to the interchange of the detection energies.[4] This demands that an angular dependency taken for $\Theta_{12} = 180°$ must be symmetric to $\vartheta_1 = 90°$. The results of such a measurement taken as a function of the scattering angle ϑ_1 for fixed difference angle $\Theta_{12} = 180°$ is presented in Fig. 1(b). The detection energies are $E_1 = 3.5$ eV and $E_2 = 0.5$ eV so that the excess energy is $E = 4$ eV. The shape of the angular dependence which is rather similar to the corresponding dependence measured with equal energies [Fig. 1(a)] is symmetric to $\vartheta_1 = 90°$ within the experimental uncertainty of $\pm 2°$. Hence, in the case of helium one can assume the threshold law to be valid at least up to 4-eV excess energy. It should be noted that in an analogous measurement on helium with $\Theta_{12} = 180°$, $E_1 = 7$ eV, and $E_2 = 1$ eV, Selles, Huetz, and Mazeau[13] found a symmetry break which was quite remarkable.

The distribution of the ejected electron energies has been investigated with high accuracy, both theoretically and experimentally, by Read and co-workers.[2,16]

In Fig. 3(a) an angular dependence of the triple differential cross section of atomic hydrogen measured with a fixed difference angle $\Theta_{12} = 180°$ is presented; the excess energy of $E = 4$ eV is symmetrically shared between the two outgoing electrons. The cross section (open circles) decreases monotonically with increasing scattering angle ϑ_1 and shows a minimum at $\vartheta_1 = 90°$ with a very small cross section, in contrast to the corresponding measurement with helium [Fig. 1(a)] where a pronounced maximum is found at this angular position. The results

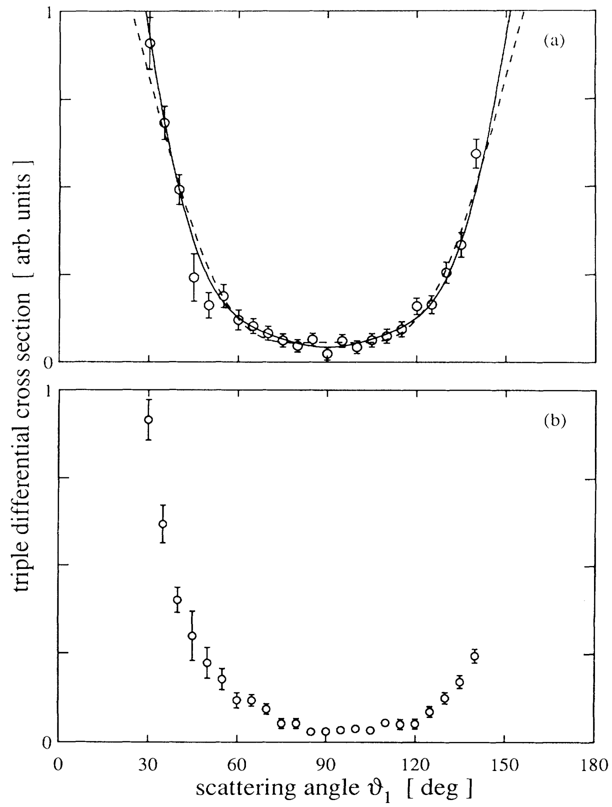

FIG. 3. Triple differential cross section for atomic hydrogen at 4-eV excess energy measured as a function of the scattering angle ϑ_1 while ϑ_2 is equal to $180° - \vartheta_1$. (a) Detection energies are $E_1 = E_2 = 2$ eV. ---, partial-wave fit including all states up to D wave; ——, partial-wave fit including all states up to F wave. (b) Detection energies are $E_1 = 3.5$ eV and $E_2 = 0.5$ eV.

of the partial-wave fit according to Altick and Rösel[15] are also shown as a broken line (fit including all states up to D wave) and as a solid line (all states up to F wave). From the fit it is obvious that the D wave must be included, but there is no clear evidence for a F-wave contribution. The quality of the fit was proved in terms of the standard deviation χ^2 which improves only from 1.5 to 1.0 when the F wave is included; for helium [Fig. 1(a)] the inclusion of the F wave changes χ^2 from 5.8 to 1.2. Although this could be attributed to the poorer statistics of the measurement, it seems to be reasonable that the F wave is less important in the case of atomic hydrogen because the number of partial waves in the incident electron beam reduces as the incident energy decreases. In Fig. 3(b) the detection energies are $E_1 = 3.5$ eV and $E_2 = 0.5$ eV. The symmetry line of the spectrum is shifted to $\vartheta_1 = 100° \pm 3°$ indicating contributions from $\{LS\pi\}$ states which are antisymmetric with respect to radial interchange. This leads to the assumption that the atomic hydrogen at 4 eV above threshold is not yet fully within the range of the threshold law.

The intensity of the antisymmetric partial waves, however, is not so large that their disappearance at threshold can cause a distinct variation of the angular distribution. That means that the angular correlations of the two outgoing electrons at threshold for helium and atomic hydrogen are drastically different although the asymptotic situation, namely, two free electrons in the field of a singly charged positive ion, is identical.

One reason for these drastic differences is the presence of an additional exchange mechanism in the case of helium, namely particle exchange where the incoming electron remains in the ion shell and both originally bound electrons leave the complex after the collision. A second reason could be the non-Coulombic field of the helium ion which strongly changes the phase shifts and therefore the interference pattern of the different partial-wave amplitudes.

Obviously the triple differential cross section depends on short-range interactions even at threshold. This is in contrast to the situation of most other scattering processes, e.g., inelastic electron-atom-molecule scattering where only the absolute normalization of the cross section depends on the intrinsic collision but not the angular behavior since only one partial wave is involved. In our opinion the experimental results presented here can only be described within the framework of an *ab initio* theory which includes the full dynamics of the collision process.

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