Triple Coincidence Experiment to Explore the Two-Electron Continuum States of the Projectile Resulting from Mutual Ionization in 100-keV He^0 + He Collisions

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The existence of the two-electron cusp in atomic collisions, i.e., the enhanced emission of two electrons in the forward direction with velocities equal to that of the projectile, has been investigated experimentally. Using a time-of-flight technique, the energies of the two electrons resulting from the simultaneous target and projectile ionization in 100-keV $He^0 + He$ collisions have been measured by detecting triple coincidence between the electrons and the outgoing He^+ ion. The coincidence yield clearly shows a peak as a function of the electron energies at the expected cusp position. Furthermore, a strong correlation was found between the energies of the two electrons, which is traced back to an angular correlation of 180° in the projectile-centered reference system.

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According to the threshold laws, the energy dependence of the cross section of a collision process in the neighborhood of a threshold energy is governed only by the type of the interaction (long- or short-range, attractive or repulsive), and it is not influenced by the detailed dynamics of the collision. This universality of the threshold phenomena was first emphasized by Wigner [1] investigating the case of two-body interactions. For atomic physics applications Wannier [2] derived a threshold law for processes that lead to final states in which two electrons escape from a positive ionic core of charge Z. He has shown that at the threshold the two-electron breakup is a highly correlated process, in which the electrons move symmetrically in opposite directions.

In the past five decades threshold processes have been the subject of numerous investigations (see Refs. [3] for a review). In the field of ion-atom collisions an extensively investigated threshold phenomenon is the electron cusp. The cusp is a peak appearing in the energy spectrum of the electrons emitted from the collision in the forward direction. It is centered at the electron velocity that matches the projectile velocity, $\mathbf{v}_e = \mathbf{v}_p$. In the projectile-centered reference frame the electrons contributing to the cusp move slowly; i.e., they occupy the low-lying continuum states around the projectile. Such states may be populated either via ionization of the projectile (electron loss to the continuum, ELC), or by capture of a target electron into a continuum state of the projectile (electron capture to the continuum, ECC). Because of the dominant role of the electron-projectile interaction, the cusp formation is governed by two-body threshold laws. The study of the cusp with different projectiles makes it possible to obtain information about the threshold laws for various types of interactions (Coulomb, dipolar, short-range, see, e.g., Refs. [4,5]).

The question naturally arises: Can low-lying *two-electron* continuum states also be populated around the projectile under suitable collision conditions? In other words, does the "two-electron" cusp exist? If so, is this process governed by the Wannier threshold law, i.e., is the emission of the two electrons highly correlated? The present work is motivated by these questions.

To our best knowledge, the first attempt to observe two electrons in low-energy continuum states of the projectile was made by Richards *et al.* [6]. Using collisions of 10.7 MeV Ag^{4+} ions with Ar atoms they detected two electrons ejected in forward direction with velocities approximately equal to the projectile velocity. The applied experimental technique, however, did not allow the independent measurement of the electron energies; therefore, the authors could not draw definite conclusions on the existence of correlation effects.

In this Letter, we present experimental data for a simpler collision system, $He^0 + He$. In the experiment, carried out at 100 keV impact energy ($v = 1$ a.u.), the energies of two electrons ejected simultaneously following the mutual target and projectile ionization were measured. The process was identified by detecting triple coincidence between the electrons and the outgoing He^+ ion. The data obtained provide the first clear evidence for the existence of the two-electron cusp. We show that the correlation observed between the energies of the electrons is consistent with the Wannier threshold theory.

The experiment was performed at the 1.5 MV Van de Graaff accelerator of ATOMKI. The scheme of the experimental setup is shown in Fig. 1. The He^0 beam is produced from the He^+ beam of the accelerator via charge exchange with the residual gas of the beam channel. The charged components of the beam are deflected away by an electric field (not shown in the figure). A collimator with a length of 50 cm defines the final He^0 beam of 0.5 mm diameter. The charged ions produced in the collimator are swept away by an electrostatic beam cleaner mounted just in front of the effusive He gas target.

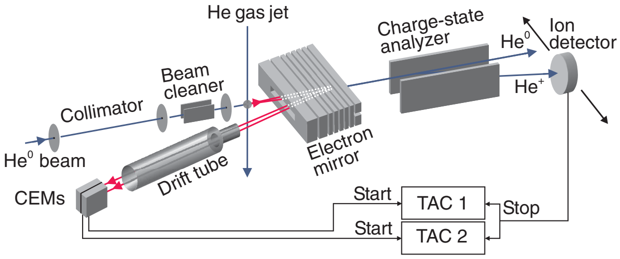

FIG. 1 (color online). Scheme of the experimental setup.

The electrons ejected from the interaction of the He^0 beam and the target in forward direction are reflected by an electrostatic mirror into backward angles (≈160°), while the projectile passes through the mirror. After being reflected, the electrons fly in a field-free space until they reach the electron detectors (two channel electron multipliers, CEMs). The outgoing projectile ions are charged-state analyzed by means of an electrostatic deflector and detected by an ion detector [7]. The energies of the two electrons are determined by measuring the time elapsed between their emission and detection. These data are obtained by measuring the time differences between the pulses of the CEMs and that of the ion detector with the use of two time-to-amplitude converters (TACs). The outputs of the TACs are digitized and stored in a computer in event list mode.

The essential part of the setup is the electrostatic electron mirror [8]. Speciality of the mirror is that it was built without applying grids in order to minimize any secondary electron production. Test experiments of the time-of-flight spectrometer were carried out for collisions of 200–350 keV C^{q+} ($q = 1, 2$) ions with Ar atoms. For the energy calibration of the spectrometer the energy of the cusp and those of the autoionization (AI) electrons from the projectile were used. The emission of an AI electron with velocity v_{AI} in the projectile frame results in two peaks in the measured energy spectrum, corresponding to forward and backward emissions with velocities $v_p \pm v_{\mathrm{AI}}$. Taking advantage of the fact that the energy of the cusp and those of the AI peaks shift with the impact energy, E_p, we obtained a large data set for the energy calibration by recording spectra at several values of E_p. From the measured widths of the AI peaks we determined the energy resolution. In the range of the present experiment (5–20 eV; cusp position: $E_{\mathrm{cusp}} = 13.6$ eV) $\Delta E/E$ varies between 6% and 10.5%.

The entrance aperture of the CEMs has a rectangular shape. The acceptance (half) angles were estimated from the size of the entrance aperture of CEMs (5×10 mm^2) and the distance of flight of the electrons (30 cm). They were found to be 0.5° and 1° in the horizontal and vertical plane, respectively. The two CEMs are located symmetrically with respect to the direction of the reflected electrons emitted originally at 0°; i.e., the two observation angles are −0.5° and 0.5°.

The choice of the process $He^0 + He \rightarrow He^+ + He^+ + e_1 + e_2$ (simultaneous ELC and ECC) is explained by the relatively large triple coincidence count rate, $\sim 0.01/\mathrm{s}$ (at a random coincidence level of about 10%). For the energetically less favored double ELC and double ECC by He^0 and He^{2+} impact, respectively, we found much smaller count rates. We note that the He^0 beam obtained by neutralization had a considerable content of metastable (primarily $2\,^1S$ and $2\,^3S$) atoms. As an estimate for the metastable fraction one may use the value $\sim 17\%$ measured by Gilbody *et al.* [9] for N_2 neutralizer. The metastable atoms in the beam enhance the probability of the simultaneous ionization of the target and projectile due to the smaller effective ionization potential. We also note that the detection of the electrons in coincidence with the outgoing He^+ ions does not exclude the double ionization of the target. However, this three-electron process probably has a negligible contribution. The ejection of the second target electron is a process of small probability due to the large ionization potential.

In a series of experiments we checked whether false (unphysical) electron-electron coincidences contribute to

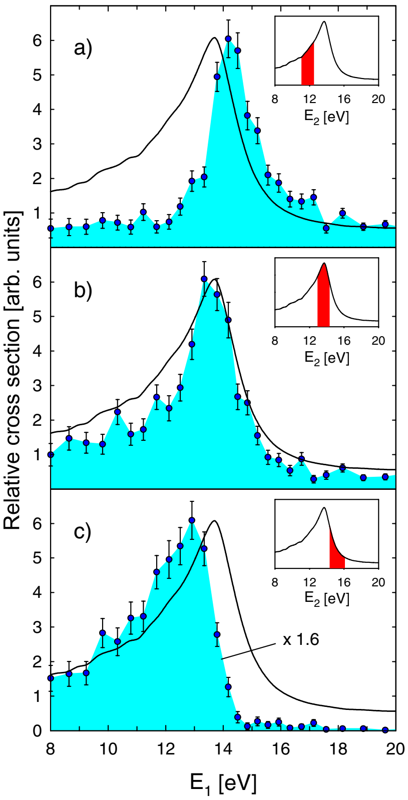

FIG. 2 (color online). Energy spectra of the electron e_1 measured at 0° for 100 keV $He^0 + He$ collision. Closed circles: e_1-e_2-He^+ coincidences. The insets show the coincidence windows: For the spectra in parts (a),(b), and (c) the energy of e_2 lies in the intervals 11.0–12.5 eV, 13–14.2 eV, and 14.5–16.0 eV, respectively. Solid line: e_1-He^+ coincidences (ELC cusp). The double and triple coincidence spectra are normalized at the peak maxima.

the true triple coincidences. To establish an upper limit for the contribution of such events, among others we measured the triple coincidence yield for double ECC by He^0 impact. In this process the forward emission of two electrons is very unlikely. No triple coincidences were observed on top of the background of random coincidences.

For the process under study, single-collision conditions were checked by measuring the triple coincidence rate as a function of the target gas pressure. We found a linear dependence.

With the use of the recorded electron energy data we determined the triple coincidence yield differential with respect to the two-electron energies. From the coincidence yield we subtracted the yield of the random coincidences and corrected it for the energy-dependent electron detection efficiencies (transmissions). The latter quantities were determined in a separate experiment (see Ref. [10]). We did not determine absolute cross sections.

In Fig. 2 we show energy spectra of one of the electrons, e_1, with the condition that the energy of the other electron, e_2, lies in a narrow range ("coincidence window"). Each spectrum shows the presence of the cusp. For comparison we displayed also the ELC cusp obtained from e_1-He^+ coincidence events. Let us denote the energy of e_1 and e_2 by E_1 and E_2, respectively. In Figs. 2(a) and 2(c) definite shifts of the peak are visible. The direction of the shift depends on E_2: The peak is shifted to higher energies when E_2 is fixed at the low-energy side of the cusp, and *vice versa*. Significant differences can also be observed in the peak shape for the different coincidence windows. For small E_2 the cusp is skewed to high energies, while the opposite behavior is seen when E_2 is fixed at the high-energy side of the cusp. When the coincidence window was set at the cusp maximum [Fig. 2(b)] the shape of the triple coincidence peak is similar to that of the ELC peak, but it is slightly narrower.

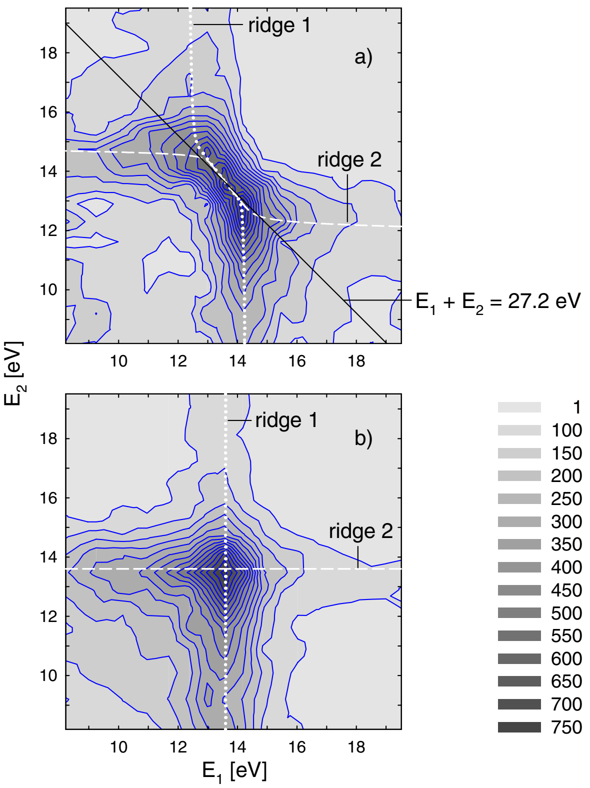

FIG. 3 (color online). Contour plots of the fourfold differential cross section (FDCS) as a function of the electron energies. Part (a) Measured FDCS. Part (b) FDCS for uncorrelated electron emission (see text).

The dramatic changes of the energy spectrum of e_1 as a function of the energy of e_2 shown in Fig. 2 are clear manifestations of the repulsive Coulomb interaction between the electrons. Since the electron emission at the low- and high-energy side of the cusp corresponds to backward and forward emission in the projectile-centered reference system, respectively, the energy correlation observed in the laboratory system is a sign of angular correlation of 180° in the projectile frame.

In order to see finer details of the strong electron correlation, in Fig. 3(a) we displayed the contour plot of the measured relative fourfold differential cross section (FDCS). For comparison, in Fig. 3(b) we displayed a contour plot that shows the case of *uncorrelated* electron pairs emission. The latter FDCS data were synthesized artificially, by taking the energies of the electron pairs from separate, independent double coincidence experiments. In both figures the distributions are characterized by two ridges. In Fig. 3(b) the ridges are perpendicular straight lines ($E_1 = 13.6$ eV and $E_2 = 13.6$ eV). As a result of the correlation, the ridges in Fig. 3(a) are distorted in such a way that instead having one crossing point, they have a joint straight line section.

In the joint section of the ridges the energies of the ejected electron pairs follow the line $E_1 + E_2 = 2E_{\mathrm{cusp}}$. At the maximum of the FDCS ($E_1 = E_2 = E_{\mathrm{cusp}}$) both electrons fly with the projectile velocity, v_p. In the case of other pairs along the joint ridge the electrons have unequal energies. Although they fly with velocities slightly different from v_p, the deviations of their energies from E_{cusp} are balanced, so the sum of the energies is constant, $2E_{\mathrm{cusp}}$. One can easily show that close to the maximum, along the ridge the center of mass energy of an electron pair with energies E_1 and $E_2 = 2E_{\mathrm{cusp}} - E_1$ can be expressed as $E_{\mathrm{CM}} \approx 2E_{\mathrm{cusp}} - (E_1 - E_{\mathrm{cusp}})^2/(4E_{\mathrm{cusp}}) \approx 2E_{\mathrm{cusp}}$, to a good approximation. Consequently, the electron pairs along the joint ridge move with center of mass velocity v_p. The two-electron emission from a moving center strongly suggests that low-lying quasistationary two-electron continuum states are formed around the projectile.

Wannier threshold theories (e.g., [11]) predict that the electron pair angular correlation is characterized by a Gaussian distribution with a maximum at $\theta_{12} = \pi$ and a full width at half maximum expressed as $(\pi - \theta_{12})_{\mathrm{FWHM}} = \alpha E^{1/4}$. Here, E is the excess energy above the ionization threshold, and α is a constant. In order to see whether our

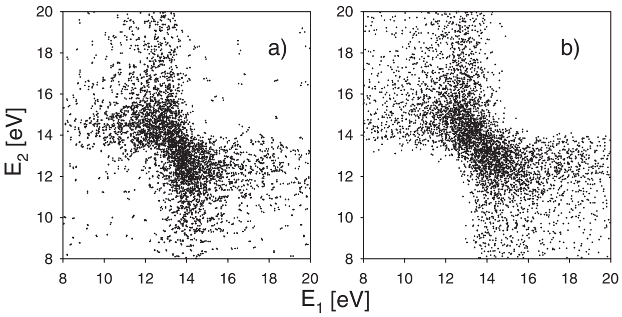

FIG. 4. Plot of the individual two-electron emission events in the $E_1 - E_2$ plane. Part (a) present experiment. Part (b) Monte Carlo simulation based on the Wannier theory.

measured data reflect the 180° angular correlation we carried out the following Monte Carlo simulation. We suppose that the final state of the collision is a correlated two-electron Wannier state centered at the outgoing projectile. For the simulation of the electron emission from this state we randomly create electron pairs with 180° angular correlation in the projectile reference frame. We assume that the electron pairs are emitted isotropically. We allow random deviations from the 180° correlation with a Gaussian distribution. For the width of the Gaussian we apply the above expression with $\alpha = 3.0$ (with E given in atomic units). The latter value was obtained by Bartlett and Stelbovics [12] for electron-impact ionization of hydrogen in a calculation based on numerical solution of the full Schrödinger equation. The $\alpha = 3.0$ result was verified recently by the experiment of Williams *et al.* [13]. In our simulation the excess energy is the total energy of the electron pair in the projectile frame, $E = E_1' + E_2'$. The energies E_1' and E_2' are obtained by a random selection of the electron velocities in the range between 0 and 0.25 a.u. Finally, the energies E_1 and E_2 in the laboratory frame are calculated by Galilean transformation of the velocities. The conditions of the "detection" of the electrons (observation and acceptance angles) are the same as in the real experiment. The time resolution, the finite projectile beam size, and the extended gas target are taken into account in the simulation.

In Fig. 4 we compare the distribution of the individual two-electron emission events obtained from the Monte Carlo simulation with that observed in the experiment. The agreement is very good. The characteristic ridges seen in the experiment and discussed above clearly appear also in the simulation. We repeated the simulation with different α values. Increasing the sharpness of the 180° correlation (i.e., decreasing the value of α) we obtained that the two ridges tend to unite into the line $E_1 + E_2 = 27.2$ eV. For small angular correlation the ridges are perpendicular straight lines [see Fig. 3(b)].

In conclusion, the present triple coincidence experiment gave the first evidence for the existence of the two-electron cusp, i.e., the enhanced emission of two electrons with approximately the projectile velocity in forward direction. We emphasize the small difference between the observation angles (~1°) for the electrons. Our finding that the "dielectron" emission is most likely governed by the Wannier threshold law opens a new dimension for the study of the near-threshold two-electron breakup process. The kinematic amplification of the electron energies resulting from the Galilean transformation (see, e.g., Ref. [5]) makes it possible, in principle, to check the validity of the Wannier threshold law in the extremely low, meV range of the electron energies. A further new possibility is that with use of highly charged projectile ions one can extend the Wannier-type studies for large values of Z, the charge of the ionic core.

Finally, we stress the importance of theoretical calculations for the full ionization process. It is an interesting question whether the present theories are capable to account for the population of highly correlated low-energy two-electron continuum states around the projectile. Further experiments mapping the electron correlation for emission angles larger than 0° are also needed to search for the limits of the validity of the proposed Wannier mechanism. Such experiments, however, could only be performed with a more advanced experimental technique (first of all, with position sensitive detection of the electrons) because of the rapidly decreasing coincidence count rate with increasing observation angle.

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