Observation of Electron Capture into Continuum States of Neutral Atoms

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Energy spectra of electrons ejected in the forward direction from 75-keV/amu He^0-He,Ar collisions have been measured in coincidence with the charge-state-selected outgoing projectiles He^0, He^+, and He^{2+}. The appearance of the cusp-shaped peak in the electron spectrum in coincidence with He^0 gives the first clear experimental evidence that electron capture into the continuum states (ECC) occurs in collisions where the projectile is a neutral atom. The ECC for He^0 impact is characterized by a considerably smaller width of the cusp peak than for He^+ impact.

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A great advantage in studies of the atomic collision processes is that the interaction between the colliding partners—the Coulomb force—is precisely known. The long-range feature of the Coulomb force, however, gives rise many times to serious difficulties in the formal collision theory as well as in the numerical solution of the scattering problems. The difficulties are particularly severe when the scattering problem cannot be reduced to a two-body problem. One of these cases is the so-called "cusp" peak appearing in the energy spectrum of the forward-ejected electrons at electron velocities v_e equal to the velocity of the projectile v. Since its discovery[1] the cusp has been the subject of a number of experimental and theoretical investigations.[2] Recent developments[3,4] indicate that satisfactory description of the phenomenon is possible only with proper representation of the scattering state by *three-body* Coulomb continuum wave functions.

The electrons forming the cusp peak may originate from two processes. Projectiles carrying bound electrons may lose them with small kinetic energy due to ionization by the target atoms. The transformation of the velocity spectrum of the electrons from the projectile reference frame to the laboratory frame results in a velocity spectrum proportional to $|v-v_e|^{-1}$.[5] This process is called "electron loss into the continuum" (ELC). The other source of the cusp electrons is a special ionization process of the target by the projectile, called "electron capture into the continuum" (ECC).[6] ECC can be understood by imagining electron "capture" into low-lying continuum states of the projectile, as a continuation of the real capture into high Rydberg states.

In this Letter we report on new experimental results for the ECC process. Using a neutral atom as a projectile we observed—to the best of our knowledge, for the first time—electron capture into continuum states of a neutral particle. For a neutral atom the Coulomb potential around the nucleus is fully screened, i.e., the interaction has short range. This circumstance is a simplifying condition for the theory, and thereby there is a better chance to solve the related three-body problem.

The present work was stimulated by former studies[7-9] directed to determine the ECC contribution to the cusp for collisions involving structured (e.g., He^+) projectiles. In a naive view of such collisions it is thought that the projectile loses its weakly bound electrons with large probability, i.e., the ELC process completely masks any "contamination" due to ECC. Measuring cross sections of the two processes for 50–150 keV/amu He^+-He,Ar collisions, we have shown[9] that this is not the case. We found that the ECC dominates the forward electron-cusp production at low collision energies (≤ 100 keV/amu).

In the above experiment we separated the two processes detecting the electrons in coincidence with the charge-state-selected outgoing projectiles, i.e., with He^+ (ECC) and He^{2+} (ELC). Coincidences with the third charge-state channel, He^0, correspond to a two-electron process in which the electrons are captured by the projectile, one into a bound state, the other into a continuum state [transfer ionization,[10] (TI)]. We did not measure this channel systematically regarding the process as a negligible, second-order one. However, as a check we made a few measurements and got a very surprising result. Comparing to the other two processes, TI produces a cusp with a considerably *reduced width.* In Fig. 1 the results obtained for a 75 keV/amu He^+-Ar collision are displayed. The figure makes a comparison between shapes of the cusps originating from ECC and TI. The width of the peak (FWHM) for TI is smaller by a factor of 3.5.

This interesting finding has motivated us to extend the measurements for neutral projectiles. Our questions were the following: (i) Does the cusp (from ECC) exist? (ii) Is there any difference in the shape of the cusp when not only the outgoing but also the incoming particle is neutral?

The experimental setup was the same as that used in our measurements with charged projectiles. It has been described in detail elsewhere,[9] and only briefly summarized here. The He^0 beam was obtained from the 1.5-MeV Van de Graaff accelerator at this institute. Before the collimation of the beam its charged components were

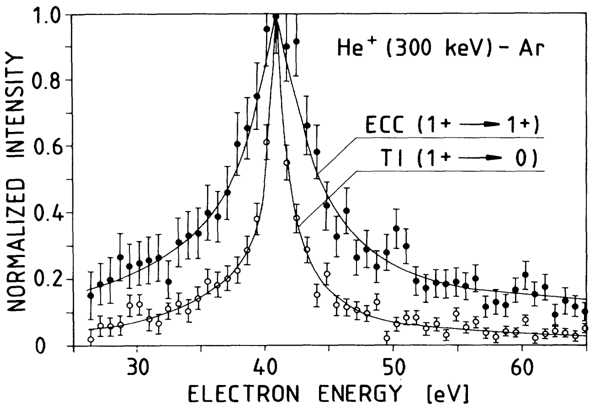

FIG. 1. Measured shapes of the electron cusps corresponding to ECC and TI processes induced by He^+ from Ar. Charge state of the incoming and outgoing projectile is indicated in the parentheses. The thin lines through the experimental data are drawn to guide the eye (also in the other figures).

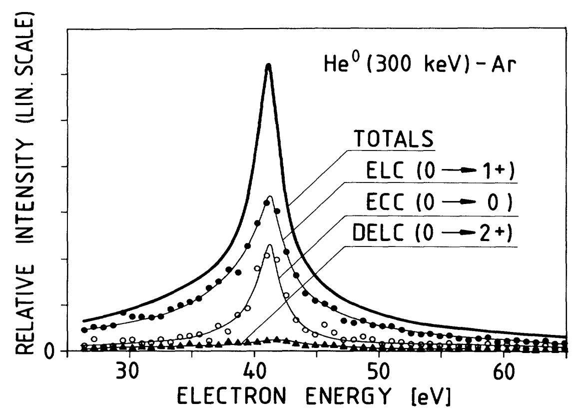

FIG. 2. Electron energy spectra obtained from He^0 on Ar collisions in coincidence with He^0, He^+, and He^{2+}.

deflected out by a pair of electrostatic deflector plates placed in the beam line. The beam passed through an effusion gas target. The forward-ejected electrons were energy analyzed by a double-stage cylindrical-mirror electron spectrometer[7] (half angle of angular acceptance $\theta_0 = 3.5°$, energy resolution $\delta E/E = 0.5\%$ and detected by a channel electron multiplier. The particle beam leaving the collision regime was charge-state analyzed by means of an electrostatic deflector. The particles of the selected component were detected by a fast detector based on collection and amplification of secondary electrons emitted from a metallic surface hit by the particles.[11] Coincidences between the electrons and the outgoing projectiles with specific charge states were established using standard fast coincidence electronic circuits. The recorded coincidence spectra were corrected for contribution from random coincidence events (measured separately), for loss of coincidence counts due to the high count rate in the particle branch, for the dark current of the channel electron multiplier, and for the overall energy-dependent efficiency of the electron detection (including the resolution correction). Care was taken to check the occurrence of double collisions, i.e., subsequent collisions on *two* target atoms. Such collisions (e.g., capture of an electron into a bound state of the projectile in one collision and its loss into the continuum in another collision, or the reversed process: loss and subsequent capture) may contribute with false coincidences to the ECC cusp. As a check we measured the coincidence count rate at several pressure values of the target gas increasing the pressure from a minimal value by a factor of 4. Proportionality was found, demonstrating that the density of the target was low enough to provide single-collision conditions.

The measurements were performed at 75-keV/amu bombarding energy, and for targets He and Ar. In Fig. 2 our results for Ar are displayed. The coincidence spectra are normalized so that their sum gives the single (total) spectrum. As is seen from the figure the dominant process (66%) is the ELC (coincidences with He^+). The cusp observed in coincidence with He^0 with surprisingly large contribution (28%) clearly proves the existence of the electron capture into the continuum states of the He^0 projectile. We remark that in a noncoincidence experiment one could hardly demonstrate the existence of the ECC for neutral projectiles because of the dominance of the ELC over ECC. Furthermore, we could observe again a two-electron process resulting in the double ionization of the projectile. Though we detected only one of the ejected electrons scattering in forward direction, we may call this process "double electron loss into the continuum" (DELC). The contribution of DELC to the total cusp yield was found to be 6%. For the He target we have obtained smaller results. In this case we could not measure the contribution from DELC because of the low coincidence yield. The measured relative intensities for ELC and ECC are 45% and 55%, respectively, i.e., here ECC *exceeds* ELC. This large contribution of the ECC channel questions the reliability of the conclusions drawn from ELC studies of similar collision systems. For example, in Ref. 12 it was supposed that for 105-keV H^0-He collision the cusp electrons originated from ELC. We think that in this collision the ECC process may contribute significantly, and therefore any detailed analysis of the properties of the cusp (intensity, width, asymmetry) and comparison with ELC theory is illusory.

In answer to our second question concerning the shape of the cusp we have again gotten an interesting result. For ECC induced by He^0 we have observed a similar reduction of the width of the cusp as for TI induced by He^+. The narrowing of the peak can be seen in Fig. 3, where shapes of the cusps originating from ECC process for positively charged (He^+) and neutral (He^0) projectiles are compared. According to the figure the effect depends on the target. For argon the width is reduced, in a

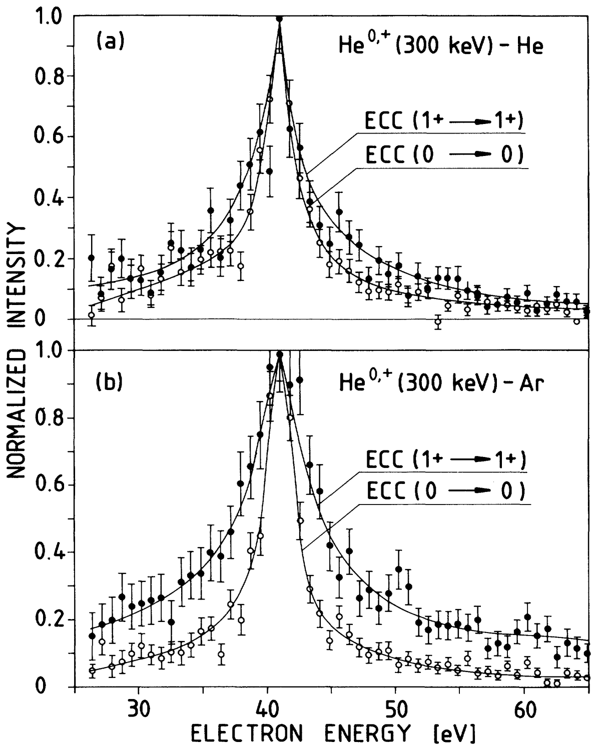

FIG. 3. Comparison of ECC cusps produced by charged (He^+) and neutral (He^0) projectiles for (a), He and for (b), Ar targets.

large extent, by a factor of 2.3 For He the reduction factor is only 1.6, but the effect is clearly seen also in this case. The target dependence may be explained by the difference of the binding energies of the electrons in the two targets, as well as by occurrence of shell effects[13] for argon.

From our experimental results we may draw the following conclusions. Let us first consider the observation that the cusps are similarly narrow for ECC at He^0 impact and for TI at He^+ impact. Since both of these scattering processes are characterized by a neutral projectile emerging from the collision, this observation strongly supports the picture that the shape of the cusp is decisively determined by the outgoing part of the projectile path. This means that it is plausible to regard the ECC as a two-step process. In the first step the projectile ionizes the target (for TI simultaneously captures one electron into a bound state) in a "normal" way resulting in electrons with a smooth energy spectrum. In the second step a post-collisional interaction takes place between the outgoing projectile and the ejected electron. The smaller the difference in their velocity $|v - v_e|$, the longer the interaction time, and thereby the larger the probability for a capture event (into a continuum state). Classically such process can be visualized as a result of a focusing effect exerted by the projectile on the ejected electrons. Keeping in mind that the capture probability depends not only on the interaction time, but also on the strength and shape of the interaction, in this picture we can also explain the observed narrowing effect. Let us compare the cases of the unscreened (V) and fully screened (V_s) Coulomb potential. For electrons with small velocity difference $|v - v_e|$ (the center of the cusp) $V \approx V_s$ holds for long time, i.e., the capture probabilities for the two cases are about the same. For large velocity differences (the tails of the cusp), however, the distance between the projectile and the electron rapidly increases. Since V_s falls exponentially with the distance, after a short time $V_s \ll V$; consequently, the capture probability decreases in a much larger extent in the case of the fully screened potential.

Unfortunately, no theory of ECC induced by neutral atoms (or generally, structured particles) exists at present. McGuire *et al.*[14] have given a simple estimate of the effect of the Coulomb screening on the sharpness of the ECC cusp. The estimation is based on the fact that for the pure Coulomb potential the cusp divergence arises from the normalization factor of the Coulomb continuum wave function. According to the authors, for a screened potential the cusp is truncated, i.e., the divergence disappears. The truncation width δk is estimated from the uncertainty principle and given as $\delta k a = h$, where k is the momentum of the ejected electron and a is the screening constant. In the limit of small values of a the cusp is infinitely broadened, i.e., no cusp exists for the short-range potential of a *pointlike* particle. The relationship, however, seems to be in contradiction with our finding, because for finite values of a it predicts *broadening* of the cusp, while we have observed *narrowing*. More systematic experimental studies and in particular precise theoretical calculations are needed to explore the physics behind the phenomenon of the ECC cusp production by neutral atoms (molecules). One of the aspects of general interest, namely, the replacement of the long-range potential by a short-range one, has already been discussed. We mention another aspect. According to the interpretation of the ECC mechanism given here, the shape of the cusp reflects to some extent the shape of the electric potential around the projectile. From such types of "scans" of the potential one may extract the electron density in the projectile. Therefore, this kind of coincidence measurements of the ECC cusp may also serve as a tool for study of the electronic structure of atomic species.

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[1]G. B. Crooks and M. E. Rudd, Phys. Rev. Lett. **25**, 1599 (1970).

[2]For a review see, e.g., M. Breinig *et al.*, Phys. Rev. A **25**, 3015 (1982); K. O. Groeneveld, W. Meckbach, I. A. Sellin, and J. Burgdörfer, Comments At. Mol. Phys. **4**, 187 (1984); M. W. Lucas and W. Steckelmacher, in *Proceedings of the Third Workshop on High-Energy Ion-Atom Collisions, Debrecen, Hungary, 1987,* edited by D. Berényi and G. Hock, Lecture Notes in Physics, Vol. 294 (Springer-Verlag, New York, 1988), p. 229.

[3]W. Meckbach, P. J. Focke, A. R. Goñi, S. Suáres, J. Macek, and M. G. Menendez, Phys. Rev. Lett. **57**, 1587 (1986).

[4]A. Salin, in *Proceedings of the Third Workshop on High-Energy Ion-Atom Collisions, Debrecen, Hungary, 1987,* edited by D. Berényi and G. Hock, Lecture Notes in Physics, Vol. 294 (Springer-Verlag, New York, 1988), p. 245.

[5]F. Drepper and J. S. Briggs, J. Phys. B **9**, 2063 (1976).

[6]J. Macek, Phys. Rev. A **1**, 235 (1970).

[7]A. Kövér, Gy. Szabó, D. Berényi, L. Gulyás, I. Cserny, K. O. Groeneveld, D. Hofmann, P. Koschar, and M. Burkhard, J. Phys. B **19**, 1187 (1986).

[8]O. Heil, J. Kemmler, K. Kroneberger, A. Kövér, Gy. Szabó, L. Gulyás, R. DeSerio, S. Lencinas, N. Keller, D. Hofmann, H. Rothard, D. Berényi, and K. O. Groeneveld, Z. Phys. D **9**, 229 (1988).

[9]A. Kövér, L. Sarkadi, J. Pálinkás, D. Berényi, Gy. Szabó, T. Vajnai, O. Heil, K. O. Groeneveld, J. Gibbons, and I. A. Sellin, to be published.

[10]L. H. Andersen, M. Frost, P. Hvelplund, H. Knudsen, and S. Datz, Phys. Rev. Lett. **52**, 518 (1984).

[11]K. Rinn, A. Müller, H. Eichenauer, and E. Salzborn, Rev. Sci. Instrum. **53**, 829 (1982).

[12]W. Meckbach, R. Vidal, P. Focke, I. B. Nemirovsky, and E. Gonzalez, Lepera, Phys. Rev. Lett. **52**, 621 (1984).

[13]L. Sarkadi, J. Bossler, R. Hippler, and H. O. Lutz, Phys. Rev. Lett. **53**, 1551 (1984).

[14]J. H. McGuire, T. Revees, N. C. Deb, and N. C. Sil, Nucl. Instrum. Methods Phys. Res., Sec. B **24/25**, 243 (1987).