# Contribution of Field-Ionized Rydberg Atoms in Observations on Convoy Electrons

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An experiment is described demonstrating that for fast-ion bombardment of thin foils, projectile Rydberg atoms and convoy electrons emerge with comparable probabilities. These Rydberg atoms can readily ionize in the fields of electron spectrometers employed for measurements on convoy electrons, producing beam-velocity electrons which contribute significantly to the "cusp electron" spectra observed. This Rydberg contribution to the shape and intensity of the cusp peak has not been taken into account in previous treatments.

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A prominent feature observed in the energy spectrum of electrons emitted in the forward direction from thin foils[1] and gas targets[2] under fast-ion bombardment is a sharp cusplike peak occurring at an energy where the electron velocity matches the velocity of the emerging ions. For fast protons or $\alpha$ particles, these "cusp" electrons (also called "convoy" electrons in the case of solid targets) are believed to originate predominantly from the capture of target electrons into continuum states of the projectile.[3] Intense experimental and theoretical efforts have been directed towards understanding the measured cusps in terms of the electron-capture-to-the-continuum (ECC) model and also in terms of a "wake-riding" model.[4] Many of the observed features lack satisfactory explanation.[5]

These difficulties prompted us to wonder how much the presence of Rydberg atoms in the beam emerging from the target could be affecting observations on convoy electrons. If electron capture can occur into continuum states lying just above the ionization threshold of the projectile, capture into bound states lying just below the ionization threshold also can be expected to occur with comparable probability (see, for example, Refs. 3, 5, 6, and 7). It is well known that such Rydberg states are readily formed in fast-ion collisions in gases (see, for example, Riviere[8]). There also exists plentiful evidence that such states play a role, for example, in the delayed emission of Lyman-$\alpha$ radiation from foil- and gas-excited fast ions[9] and in the "Coulomb-explosion" patterns observed for $H^-$ arising from fast $HeH^+$ projectiles and for $H^0$ from fast $OH^+$ projectiles.[10]

The fate of Rydberg atoms emerging from a target will depend sensitively upon details of the experimental apparatus. Rydberg atoms have long radiative lifetimes, but they can be ionized in quite modest electric fields (see, for example, Littman and co-workers[11]). Certainly the electric fields used in most electrostatic electron spectrometers (and the equivalent Lorentz field in most magnetic spectrometers) suffice to ionize a large fraction of Rydberg atoms entering the spectrometer. It is customary in measurements on convoy electrons to pass the projectiles emerging from the target through the spectrometer. If ECC electrons and Rydberg atoms were to emerge from the target in comparable numbers, the intensity and shape observed for the cusp peak would depend critically on experimental parameters such as the spectrometer fields (their magnitudes and directions), the quality of the vacuum, the distance from target to spectrometer, etc. In the experiments described below, we show that for fast $He^+$ bombardment of carbon foils, Rydberg atoms do indeed contribute significantly to the cusp peak (similar results have also been obtained for $H^+$, $Ne^+$, $H_2^+$, and $HeH^+$ beams).

After acceleration in Argonne's 4.5-MV Dynamitron the ions were magnetically analyzed and collimated so that upon entering a vacuum chamber ($2\times 10^{-7}$ Torr), the beam-spot size was 1 mm and the angular divergence was $\pm 0.15$ mrad (see Ref. 10). In the chamber (Fig. 1) the beam first traversed a monitoring system consisting of a rotating chopper with a detector for scattered projectiles. The beam then passed consecutively through two sets of mutually orthogonal ($Y$ and $X$) electrostatic deflectors, a foil target, a further set of electrostatic deflectors ($X$), the entrance aperture of a 45° parallel-plate electron spectrometer,[12] and finally a hole drilled in the back plate of the spectrometer. The spectrometer was located so as to view electrons emerging from the target parallel to the incident beam and was oriented so that analyzed electron trajectories lay in the $X$-$Z$ plane. The foil target and the

 

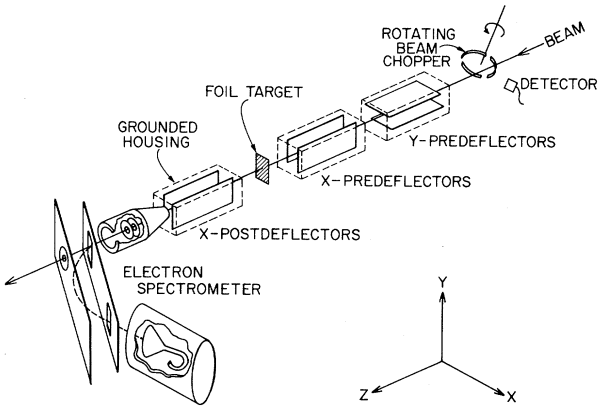


FIG. 1. Schematic arrangement of the elements of the experimental setup within the target chamber.

housings for the deflectors and spectrometer were all electrically grounded. The 3.7-mm-diam entrance nozzle of the spectrometer abutted the post-deflector housing and was located 15.8 cm downstream from the target. An entrance aperture in the housing of the post-deflector limited its angular acceptance to ±180 mrad.

Figure 2 shows electron distributions obtained with a 3-MeV $He^+$ beam and a 2-$\mu g/cm^2$ carbon target (qualitatively similar results were also obtained with the other ion beams and also with Al targets). The experimental procedure was as follows. First, with all deflector plates grounded, an electron spectrum was recorded and the cusp peak identified. Then the yield of cusp electrons was maximized by applying voltages to the predeflectors, thereby fine tuning the direction of the incident beam. (A limited angular distribution for the cusp electrons was obtained in this way.) Figure 2(a) shows the electron energy spectrum obtained after this alignment procedure. Next, a field was applied symmetrically to the post-deflector plates. Figure 2(b) shows the relative yield of electrons detected as a function of the fields in the post-deflector and the spectrometer. The deflection of the emerging projectiles in these measurements was negligible (for $He^{++}$ it was ~1/4000 of the deflection of electrons coming from the target).

Except for the cusp electrons, the electron yield varies with post-deflector field as expected for electrons originating from the target. The behavior of the cusp electrons, on the other hand, is quite different. There appear to be two components in the cusp. The first component varies with post-deflector field in the manner expected for target electrons. The second component behaves very differently. It is much less affected by the post-deflector field and appears as a "ridge" in Fig. 2(b). Figure 3 shows the distribution that results when the ridge is subtracted.

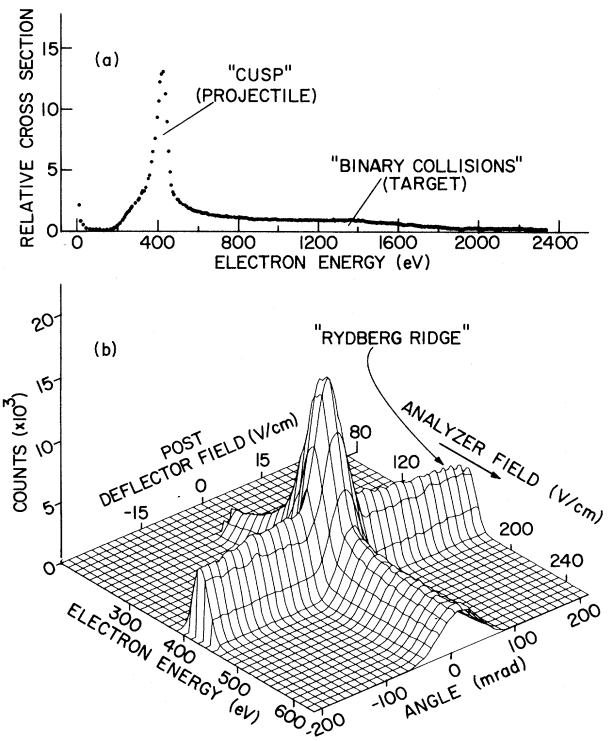


FIG. 2. Electron distributions measured for 3-MeV $He^+$ incident on a 2-$\mu g/cm^2$ carbon foil. (a) Electron energy distribution obtained in the forward direction. The peaks corresponding to cusp electrons and to binary encounters with target electrons are marked. (b) Distribution of electrons detected as a function of the post-deflector and spectrometer fields. The energy scale applies to electrons from the target. The angle scale applies only to cusp electrons (~ 400 eV) coming from the target. Note that such electrons must be emitted at an angle less than 180 mrad to the beam in order to be detected. The distribution in (a) was derived by dividing the measured electron counting rates by the electron energies in order to take into account the energy dependence of the spectrometer acceptance. This correction has not been applied in (b).

With use of a biased filament as a collimated monoenergetic source of 400-eV electrons at the target position, the response function of the detection system was measured in terms of the spectrometer and post-deflector fields. The result, which agreed well with calculations based on the known geometry of the apparatus, was then used together with a theoretical model[13] for the ECC electrons to derive the calculated curves shown in Figs. 3(b) and 3(c). Although our reso-

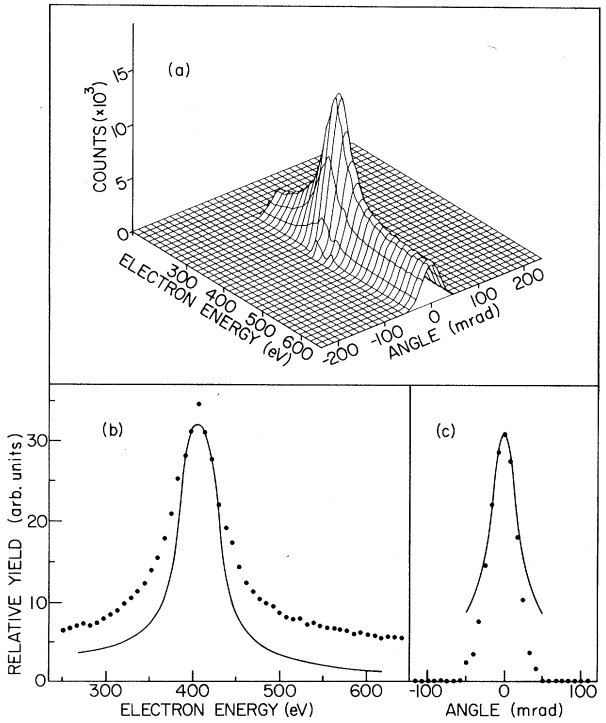


FIG. 3. (a) Distribution as in Fig. 2(b), but with the "Rydberg ridge" subtracted out. Since all of the electrons in the remaining distribution are assumed to emerge from the target, the data are plotted in terms of electron energy and angle of emission. (b), (c) Orthogonal cuts made at the peak position and parallel to the two axes of Fig. 3(a). The solid curves are energy and angle distributions calculated for ECC electrons. As in Fig. 2(a), the distribution shown in (b) has been divided by the electron energy.

lution (full width at half maximum) in energy (~8%) and angle (~24 mrad) was not good enough to test details of the ECC theory, the calculated curves are consistent with a description of the cusplike peaks in both energy and angle as being due to ECC electrons. The narrow peak in angle agrees with that determined with the predeflectors. There have been few determinations of angular distributions for cusp electrons from foils. However, our results do show qualitative agreement with the narrow angular peaks observed by previous workers.[14,15]

We identify the "ridge" electrons in Fig. 2(b) as arising from Rydberg atoms created at the exit surface of the target foil when emerging helium projectiles capture target electrons into bound states. These atoms fly undeflected ($He^0$) or almost undeflected ($He^+$ and $He^-$) into the electron spectrometer which, if set to record ~400-eV (cusp) electrons, contains a field of 170 V/cm.

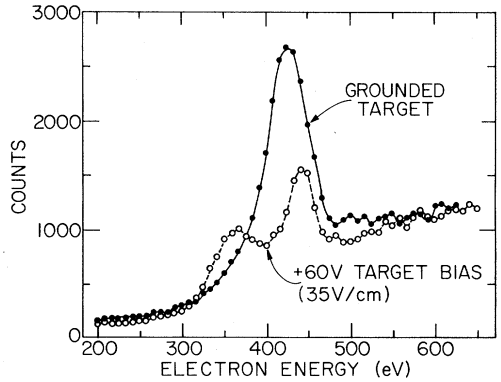


FIG. 4. Distributions of apparent energies for 0° target electrons resulting from 750-keV proton impact on a 2-$\mu g/cm^2$ carbon foil. The solid curve was measured with the target grounded. The dashed curve resulted when a positive bias was applied to the target, lowering the energies of target electrons by 60 eV.

For hydrogenic Rydberg atoms, this field reduces the ionization lifetime to about 1 nsec for $n = 50$ (and, of course, shorter lifetimes for higher principal quantum numbers).[16] Since 3-MeV helium atoms travel about 1.2 cm in a nanosecond, we can expect that the spectrometer field will ionize all Rydberg atoms with $n$ values greater than about 50. The weaker electric field in the post-deflector [up to about 30 V/cm for the data shown in Fig. 2(b)] will only ionize Rydberg atoms with much higher principal quantum numbers. As expected, the "Rydberg ridge" decreases with increasing post-deflector voltage. At a post-deflector field of 170 V/cm, the ridge height is ~1/20 of its value at a field of 30 V/cm. The center of the Rydberg ridge is displaced upwards in apparent energy by about 18 eV from the energy at the peak of the cusp shown in Fig. 3(b). The upward shift in apparent energy is due to the field ionization occurring after the Rydberg atoms penetrate on the average about 2 mm into the spectrometer field. This distance is reasonable when viewed in terms of the lifetimes quoted above and in terms of the spatial extent of the transition field at the entrance to the spectrometer.

Additional measurements in which a positive bias voltage was applied to the target confirm the origins of the two components—the apparent energy of the ridge electrons is unaffected while the electrons from the target are lowered in energy (see Fig. 4). Our experiments thus far have not permitted an accurate determination of the ratio of Rydberg atoms to ECC electrons, but the

data do indicate that in measurements where the exiting beam traverses the electron spectrometer, the two components can be expected to contribute with comparable probabilities.

In further studies, we have observed similar effects for gaseous as well as solid targets and for an extended range of beam velocities. The use of molecular-ion projectiles was also found to have a pronounced influence upon the relative numbers of Rydberg atoms reaching the spectrometer.

In comparing observations on ECC electrons either with theory or with results from other laboratories, it is clearly essential to consider the contribution of electrons stemming from the field ionization of projectile Rydberg atoms during passage through the spectrometer. Such electrons, which can influence the observed yield and shape of the cusp peak in a very significant manner, have not hitherto been taken into account.

These results have consequences in several areas of collision physics. For example, it is interesting to speculate that the well known and as yet unexplained differences in the charge-state distributions attained by fast heavy-ion beams after traversing gaseous and solid targets may be in large measure due to field ionization effects present at the exit surface of foils but absent in gases.

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