Experimental Separation of Electron-Electron and Electron-Nuclear Contributions to Ionization of Fast Hydrogenlike Ions Colliding with He

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Recoil momentum spectroscopy has been used to distinguish experimentally between contributions to the ionization of hydrogenlike O and F projectiles from interactions with the electrons and with the nucleus of a target He atom. The electron-electron contribution is separated from the nuclear one in the final momentum space of the recoil He ion, and is found to produce much smaller recoil momenta, both transverse and longitudinal, than the nuclear process. The relative contributions of the two mechanisms are consistent with theoretical expectations.

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When a fast, hydrogenlike ion encounters a light neutral target, electronic transitions in the ion can be caused by two mechanisms. The first involves interactions between the screened target nucleus and the projectile electron; the second involves interactions between the target electrons and the projectile electron [1–4]. These processes are hereafter referred to as *eN* and *ee*, respectively. The *eN* mechanism is generally the more important process and historically the more thoroughly studied. The *ee* interaction allows the target electrons to act as quasifree electrons and obey kinematic conditions appropriate to the interaction of nearly free electrons with the projectile.

The contributions of *ee* mechanisms to ion-atom collisions have received a great deal of attention in recent years as analogs of similar mechanisms involving truly free electrons. Resonant transfer and excitation (RTE) and radiative electron capture (REC) [5] have been studied as counterparts to the free-electron processes of dielectronic recombination and radiative capture. The production of binary encounter electrons [6] has been studied as an analog of elastic scattering in electron-ion collisions. The contribution of the *ee* process in these ion-atom processes was readily identified either through the resonance behavior of the cross sections or through the characteristic energies of the emitted electrons or x rays. The *ee* contribution to projectile excitation was clearly identified by Zouros, Lee, and Richard [7] via the threshold behavior of channels which should not be excited in the *eN* process but which are strong in the *ee* process.

Experimental signatures unique to the *ee* process have proved more elusive in the case of projectile ionization. The probability amplitudes for the ionization of a hydrogenlike projectile by a neutral target were first separated into the *eN* and *ee* contributions within the Born approximation by Bates and Griffing in 1954 [1]. The topic was subsequently addressed theoretically by Anholt [3], McGuire, Stolterfoht, and Simony [2], and Montenegro *et al.* [4]. Experimental evidence for the *ee* process was first seen in total cross section measurements [8,9]. The *ee* process has a threshold at an ion velocity approximately equal to the threshold electron velocity in the corresponding free-electron ionization. This threshold is rendered less precise in the ion-atom case due to the momentum distribution of the target electrons (Compton profile). Hülskötter *et al.* [8] reported enhancements in the ionization cross section for hydrogenlike C and O in collisions with He and H_2 above this threshold velocity, and showed that the excess of cross section above what one would expect for *eN* ionization could be attributed to the *ee* contribution. Montenegro *et al.* [10] have made a clearer separation of the *ee* and *eN* processes for ionization of He^+ by He and H_2 by isolating at high velocity the reaction channel for which the *ee* mechanism dominates.

Montenegro *et al.* [11] reported evidence for the influence of the *ee* interaction in the scattering angle dependence for ionization of C^{5+} and O^{7+} by He and H_2. Their experiment is the precursor of the present one, in that it embodies the idea of using the momentum transfer to distinguish between the *ee* and *eN* processes. This experiment differs in that the momentum transfer to the recoil rather than to the projectile is used, and in that both transverse and longitudinal momenta are measured. Indeed, the longitudinal momentum transfer provides the more important separation of the two mechanisms. The purpose of the present Letter is to report that measurement of the momentum of the target recoil provides a clear separation of the *ee* and *eN* contributions to ionization, from which the relative intensities of these two processes can be extracted.

The basic idea of the separation of the mechanisms lies in the fact that the *eN* interaction throws the recoil He ion forward while the *ee* interaction leaves it nearly at rest. If the ionization of the projectile occurs through a single interaction with the screened nucleus of the He, conservation of energy and momentum between two collision partners, consisting of the He system, on one hand, and the projectile (nucleus-plus-electron) system, on the other hand, lead to the result that the He recoil is thrown

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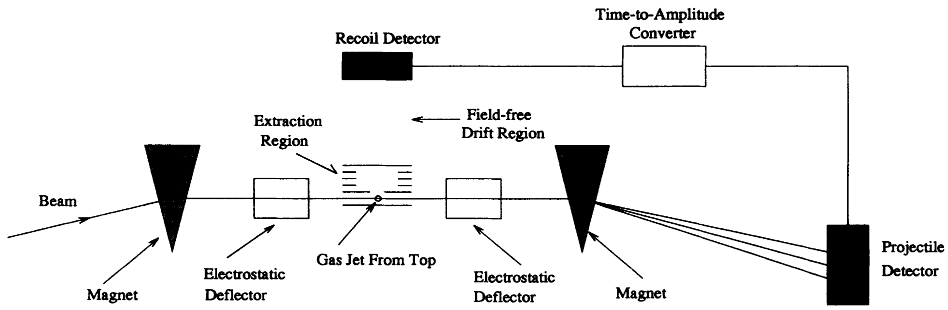

FIG. 1. Schematic of apparatus.

forward with a longitudinal momentum P_z given by Q/v. Here v is the projectile velocity and Q is the magnitude of the electronic energy which the projectile must receive to be ionized, as measured in the projectile rest frame, and is the sum of the ionization energy of the initially bound projectile electron plus the energy in the projectile continuum in which this electron finally finds itself. Small scattering angles are assumed in the derivation of this result. On the other hand, if the ionization of the projectile occurs through an interaction between a target electron and the projectile electron, the remaining He^+ ion is only a spectator in the collision and is left mostly at rest. It may be immediately noted that, while the *ee* process naturally leaves a He^+ ion, the *eN* will leave a neutral He unless some other interaction also ionizes the He atom during the same collision. If this interaction is that between the projectile nucleus and one of the He electrons, it would be described within a Born approximation formalism as a second order process. It is nevertheless a very probable process in such a collision because the projectile charge is so large and because the projectile must pass quite close to the He nucleus in order to be ionized. Thus the He target usually is ionized in the collision, independent of whether the *ee* or *eN* process is responsible for the projectile ionization.

The experiment was carried out in the J. R. Macdonald Laboratory at KSU. Beams of F^{8+} ions (37.6 and 66.1 MeV) were obtained from the LINAC, while O^{7+} (20 to 40 MeV) beams were obtained from the tandem Van de Graaff accelerator. The beams passed through a target He jet collimated so that the thermal momentum of the He target along the beam direction was limited to approximately 1.5 a.u. (see Fig. 1). He ions produced in the collision region were extracted at right angles to the beam by an electric field of about 5 V/cm and sent onto the face of a position sensitive channel-plate detector. The projectiles were charge state analyzed and detected by a second position sensitive channel-plate detector located 4 m downstream. The major charge state selection was accomplished by magnets located 0.5 m before and after the collision chamber, while additional charge state selection was provided by electrostatic deflectors centered 0.05 m before and after the jet and deflecting in the plane normal to that of the magnetic deflection. The main beam was prevented from reaching the projectile detector by a beam block, while projectile ions which had either gained (capture) or lost (loss) electrons were detected. The flight time between the detection of the projectile and the recoil and the position at which the recoil hit on the recoil detector were used to determine the recoil charge state and all three components of its vector momentum. Corrections for events in which a projectile changed its charge in one collision and ultimately produced detected He ion in a second collision were made using the deflection system to isolate double collision contributions.

The results for F^{8+} projectiles are shown in Fig. 2 as a density plot of events in which a He^+ ion is produced in coincidence with a F^{9+} ion. The two axes are the mea-

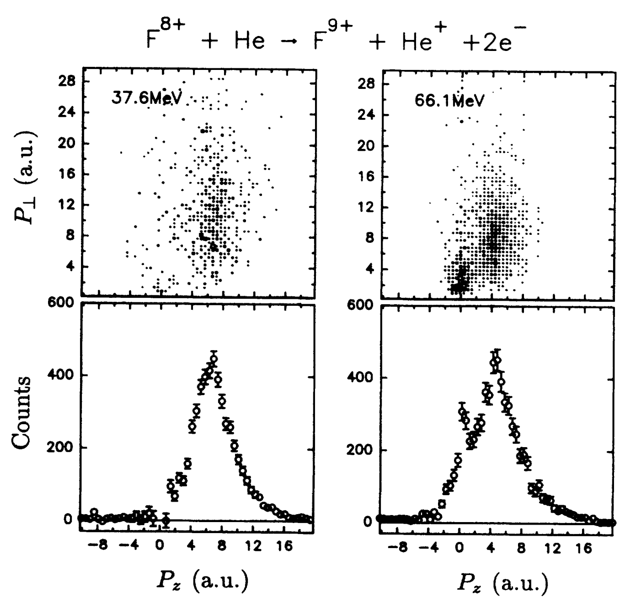

FIG. 2. Density plots, and corresponding P_z projections, of recoil momentum distributions for F^{8+} on He. The longitudinal and transverse momenta of the He^+ ions are denoted by P_z and $P_\perp$, respectively.

sured transverse (ordinate) and longitudinal (abscissa) momenta of the recoil He^+ ion. For this collision system the *ee* threshold for ionization of the projectile is at 38 MeV, and the P_z corresponding to ionization of an electron from the projectile into a zero energy continuum state is 4.55 a.u. for a beam energy of 37.6 MeV. The density plot for the lower beam energy is dominated by a single group extending from near this P_z (slightly shifted by finite resolution effects) to larger values, as would be expected for the *eN* mechanism. For the 66.1 MeV data, a second contribution appears near $P_z = 0$, which we attribute to the *ee* interaction. This contribution also is accompanied by much smaller transverse momentum transfer than the *eN* contribution, as would be expected, since the He nucleus must pass very near the F^{8+} nucleus to ionize the F via the *eN* interaction (at an impact parameter of ~ 0.1 a.u.), while the *ee* process can occur at impact parameters of the order of the size of the He wave function (~ 0.5 a.u.).

In Fig. 3 we show corresponding recoil longitudinal momentum spectra for O^{7+} on He. Projectile ionization and capture are both shown, and the data are plotted as functions of the effective exoergicity (for capture) or endoergicity (for loss). The threshold energy for the O^{7+} system is 25.6 MeV, and the ionization data reveal the growth of a second peak, or shoulder, near $P_z = 0$ for projectile energies above this energy. The spectra for capture show that capture to the projectile *L* and higher shells dominates. The single capture process is exoergic, and thus P_z has a sign opposite to that attending projectile ionization (the recoil goes backwards). Since single capture is genuinely a two-body process, the narrowness of the peaks for this channel place an upper limit on the experimental resolution of the experiment, corresponding to a P_z width of 1.5 a.u. (FWHM). The broader peak widths seen for both the *ee* and *eN* mechanisms for projectile loss are caused by the physics of the processes, not the experimental resolution.

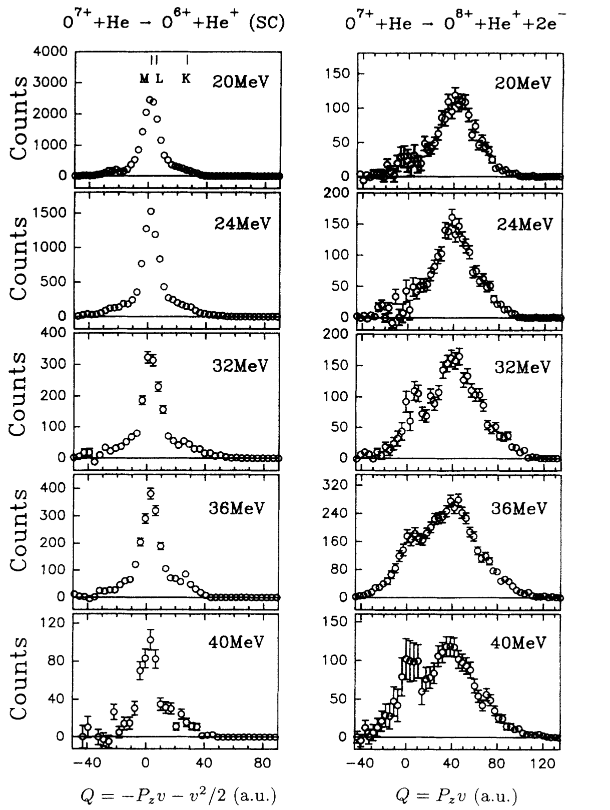

FIG. 3. Longitudinal recoil momentum spectra for O^{7+} on He. For electron capture, shown on the left, $Q = -P_z v - v^2/2$ is the exoergicity of the collision; the locations of expected Q values for capture to the *K*, *L*, and *M* shells of O^{7+} are indicated. For electron loss, $Q = P_z v$ is the endoergicity of the collision if the projectile electron energy is measured in the projectile frame.

We have extracted the ratio of the cross section for projectile ionization via the *ee* process to that via the *eN* process by evaluating the ratios of the corresponding yields in two dimensional spectra such as shown in Fig. 2. These spectra require a coincidence with a He recoil ion, but ionization of the target does not always accompany projectile ionization via the *eN* process. Following an independent electron description, we assume that for the *eN* process the removal of a target electron occurs independently of projectile ionization with an impact parameter averaged probability *P*. We note that because the projectile electron is much more tightly confined than the target electrons it is unlikely that *P* varies much over the range of impact parameters where the *eN* process occurs. *P* was deduced from the ratio of He^+ to He^{2+} yields in the *eN* region for each spectrum. It depends on the system and velocity, ranging from 0.38 at 40 MeV to 0.59 at 20 MeV for O^{7+} colliding on He. The total *eN* yield was then taken as the sum of the measured He^+ and He^{2+} yields plus a contribution from the unobserved neutral channel calculated from the above *P*. The neutral contribution represented a maximum of 38% for the case of 40 MeV O^{7+} on He. We assume that for the *ee* process the He is always ionized [10]. The total *ee* yield was therefore simply the sum of the experimental contributions from the He^+ and He^{2+} channels. The former was observed to be by far the stronger in all cases.

The resulting *ee*/*eN* cross section ratio is plotted versus beam energy in Fig. 4 and compared to the theoretical results of Hülskötter *et al.* [8]. In order to include the effect of the He Compton profile, we have also calculated this ratio ourselves. The *eN* cross section was calculated by scaling the plane-wave Born approximation ionization section for H^+ on H collision [9]. The *ee* cross section was calculated by folding the free-electron ionization cross section (Coulomb-Born-exchange calculation) [12] into the Hartree-Fock Compton profile of He [13] using the impulse approximation [9]. The resulting ratio, also shown in Fig. 4, is very close to both the data and the result of Hülskötter *et al.*

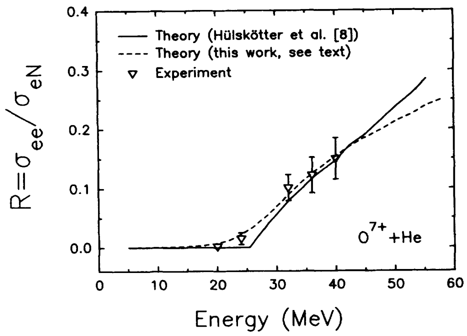

FIG. 4. The ratio of cross sections for the *ee* (σ_{ee}) and *eN* (σ_{eN}) processes as deduced from the present data is shown as open triangles. Theoretical curves are from Hülskötter *et al.* [8] (solid line) and from a calculation described in the text (dashed line).

In summary, we have used recoil momentum spectroscopy to separate experimentally contributions to the ionization of O^{7+} and F^{8+} by the nucleus and by the quasi-free electrons of a He target. The results reveal the power of recoil momentum spectroscopy to separate mechanisms which are difficult to distinguish by other methods. The cross section ratios for the oxygen case are found to be in good agreement with theoretical expectations.

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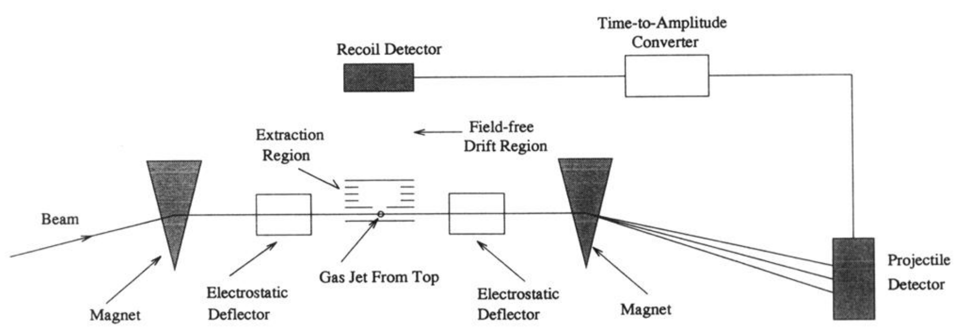

FIG. 1. Schematic of apparatus.