Angular Distribution of Fast Protons from Singly and Doubly Ionizing Collisions with He

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Angular distributions of 3–9-MeV protons scattered in singly and doubly ionizing collisions with He have been measured. A sharp shoulder is seen at 0.55 mrad, a feature attributed to binary encounters between the projectile protons and quasifree target electrons. The ratio of double to single ionization of He is found to be nearly independent of scattering angle between 0.25 and 0.55 mrad and to have a value near 2%, substantially lower than the ratio found in photoionization producing fast ejected electrons with the same energies.

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When He is ionized by either photon or charged-particle impact, it occasionally occurs that both electrons are removed. The study of the ratio (R) between double and single ionization has been the center of considerable interest in recent years,[1-13] largely because this ratio is a sensitive probe of the correlated motion of the two electrons, and cannot be treated with an independent-electron model. In this Letter, we present measurements of R for which hard collisions between charged-particle projectiles and target electrons are selected experimentally. In such a process, it is possible to impart a large energy (E_e) to one electron (hereafter referred to as the "fast" electron) without the requirement that this electron receive any momentum from its interaction with the recoiling He^+ system.[2,3] This is in contrast to the photoionization case, for which large E_e requires that the electron acquire a large momentum by imparting an equally large but oppositely directed momentum to the He^+ recoil, since the photon carries little momentum into the collision. If we call the magnitude of the He^+ recoil momentum q, large q in photoionization can be obtained only if the initial wave function for the relative motion of the electron and the recoil has large momentum components present, and only those components participate for large E_e. On the other hand, if the fast electron is removed by a hard electron-proton collision, large q is not required. Thus this experiment probes the He wave function in a region of momentum space different from that addressed in photoionization.

We restrict our attention to situations for which E_e is large compared with the He binding energy. In the absence of correlations in the He wave functions, double ionization can occur by simple "shakeoff"[1] whereby the $1s$ electron which remains after the removal of the fast electron is left in a state with a finite overlap with continuum states of the He^+ ion, and is thus "shaken" into the continuum. The value of R from such a process is independent of q, and the resulting R should not depend on whether the primary electron is removed by a photon or by a hard collision with a charged particle. If correlations in the He wave function are important, R will depend on q and will not be the same for the two cases. The present experiment allows the appropriate experimental comparison. We note that there is previous evidence that correlations are important from the result that the measured value of R in photoionization, near 5% for photon energies above 150 eV,[9-11] is considerably larger than the theoretical shakeoff value of about 0.5%.[1,2,4] This result is in agreement with calculations which include correlations in the initial[4-6] and final[6] He wave functions.

Although there is a great deal of experimental information on charged-particle ionization of He, no previous data are available for collisions in which an electron is suddenly removed by a hard collision with the projectile. The total cross sections for impact by protons, electrons, and antiprotons[12] have been measured and recent calculations by Reading and Ford[13] are in near quantitative agreement with the data. However, these cross sections are dominated by low-E_e final states, as discussed by McGuire,[7] and experimental values of R for this case are typically about an order of magnitude smaller than for high-energy photoionization. Inelastic electron scattering at low momentum transfer to the projectile has been used to determine optical oscillator strengths for ionization of He and yields values of R in excellent agreement with photoionization results.[10] For the large incident electron energies and small scattering angles used, the matrix elements and q values for the electron scattering are almost the same as those for photoionization, and thus these experiments could be considered as measuring nearly the same quantities as photoionization.

In the present experiment we have used a kinematically controlled collision between a fast proton and the He to identify hard collisions between the projectile and quasifree electrons in the target. Using binary kinematics to calculate that primary electrons with large E_e are created, we have measured R as a function of E_e for such collisions.

The experiment consisted of scattering protons with energies between 3 and 9 MeV from He and experimentally selecting the charge-state–analyzed He recoil in

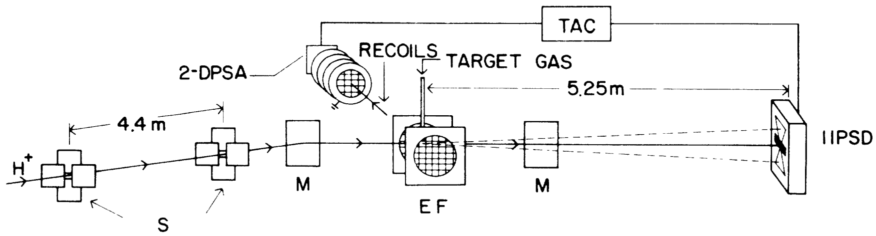

FIG. 1. Schematic of apparatus. S denotes adjustable slits, 2-DPSA is the two-dimensional position-sensitive anode, EF is the extraction field, M denotes magnets, and IIPSD is the ion-implanted position-sensitive detector.

coincidence with the projectile scattered at a determined angle between 0.1 and 1.0 mrad. It is useful at the outset to ask how a proton can be scattered to these "large" angles. (Most of the total ionization cross section lies at smaller angles.) It can scatter either from the He nucleus or from one of the target electrons. Coulomb scattering of a 3-MeV proton at 0.3 mrad from the He nucleus requires an impact parameter of 6×10^{-2} a.u., and will rarely cause an ionization of the He in the same collision. A semiclassical-approximation calculation gives an ionization probability of only 9.6×10^{-3}.[14] Scattering to 0.3 mrad from a free electron requires an impact parameter relative to the electron of 2.6×10^{-2} a.u., only a factor of 2 smaller, and will impart an energy of 540 eV to the electron so that the ionization probability will be 100%. On the basis of this simple picture, one might expect that events in which both a scattering at such a large angle and an ionization of the He occur should be dominated by the latter process. Because of the large proton- to electron-mass ratio, the scattering from free electrons can result in at most a 0.55-mrad deflection of the proton, and indeed should produce a sharp discontinuity in the angular distribution at this angle. Thus an experimental signature of binary collisions with the target electrons should be a sharp dropoff of the scattering distribution at this critical angle.

The experimental apparatus used is shown in Fig. 1. A proton beam from the Kansas State University tandem was collimated by $0.1\times0.2\text{-mm}^2$ slits located 4.4 m apart, deflected by a magnet, and sent through a gas jet of He with a target thickness below 1 mTorr-cm. The scattered protons were charge selected and detected by an ion-implanted one-dimensional position-sensitive detector located 5.25 m beyond the target and having a spatial resolution of 0.1 mm. The detector was collimated by a bow-tie–shaped aperture which projected the radially symmetric angular distribution onto one dimension. Since the azimuthal angle was limited to 22.5° from the detector axis, the radial distance from the beam center differs from the distance along the detector axis by an average of only 3%, and the position spectrum is thus nearly proportional to $d\sigma/d\theta$.[15] The measured overall angular-resolution function had a FWHM of typically 50 μrad. The direct beam was prevented from reaching the detector by a 1-mm-diam rod placed perpendicularly across the center of the bow tie, so that only protons scattered outside 0.1 mrad were detected. The He recoils were ejected at right angles to the beam by a transverse electric field of 500 V over 8 mm and, after drifting 70 mm further, were detected by a large (3 cm diam) position-sensitive channel-plate assembly with a resistive anode encoder. Singly and doubly ionized ions were separated by their different flight times. The $[He^{++}]/[He^{+}]$ ratio was found not to be gas-pressure dependent within experimental error, although substantial charge exchange of He^+ with He is expected within the jet. Since the He^+ is only thereby replaced by a slow He^+, the He^+ is not lost and the net effect is only to broaden the He^+ time peak, not to lose area from it.

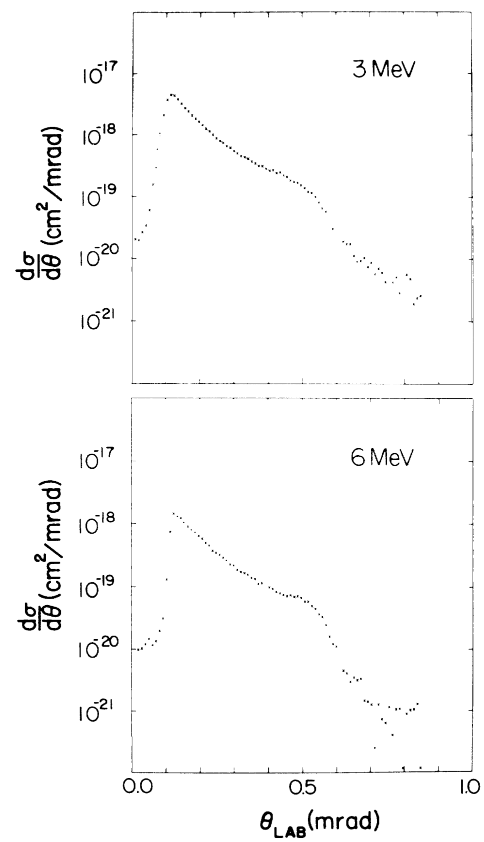

FIG. 2. Angular distributions for singly ionizing collisions only for protons on He.

Figure 2 shows angular distributions of events in which the He is singly ionized. Absolute scales were assigned by normalization to the singles recoil counts and by use of known total cross sections for ionization of He by protons.[16] There is a clear dropoff at the critical angle of 0.55 mrad. We interpret this as experimental confirmation that these large-angle ionizing events are dominated by scattering from the target electrons, not from the He nucleus. The sharp dropoff at 0.55 mrad is expected to be slightly washed out by the momentum distribution of the target electrons. As expected, this effect is seen to be relatively more important at 3 MeV where this momentum is larger relative to the momentum transferred to the projectile for a given scattering angle. These distributions are in good agreement in shape and magnitude both with a first-Born-approximation calculation of the ionization,[17] which is dominated by the so-called "Bethe ridge" in this angular region,[18] and with a simple Rutherford scattering from free electrons, as will be discussed in a separate publication.

In Fig. 3(a) we show R plotted versus scattering angle. These data represent averages over several running days and gas pressures. In Fig. 3(b) the same data, for angles inside 0.55 mrad, are plotted versus E_e, where E_e is taken to be the energy imparted in a binary encounter of the proton with a free electron at the appropriate scattering angle. We choose to present our data in this form because the importance of scattering of the fast electron with the remaining electron should be primarily dependent on E_e and thus a comparison of these data with the photoionization data at E_e equal to the photoelectron energy seems appropriate. In the present experiment, R is substantially lower than that found in photoionization for the same E_e and is only weakly dependent on either the proton energy or E_e. Although the 6-MeV data appear to lie somewhat below the 3-MeV data, it is not clear that this is an important trend. An average of R over scattering angles between 0.25 and 0.5 mrad yields $2.24\% \pm 0.05\%$, $1.85\% \pm 0.06\%$, and $2.03\% \pm 0.35\%$ for proton energies of 3, 6, and 9 MeV, respectively.

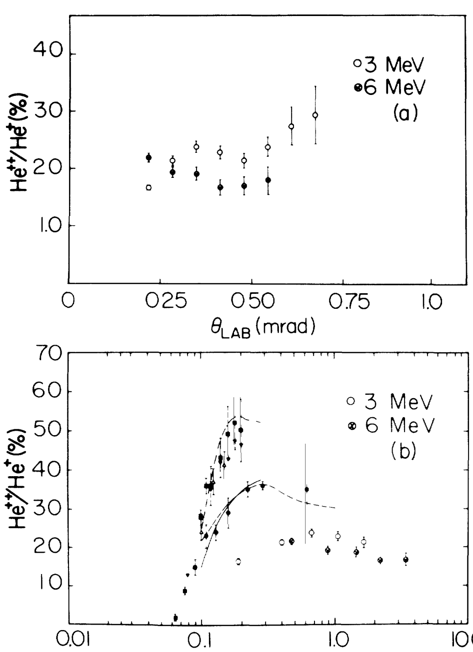

FIG. 3. (a) The ratio R of double to single ionization vs scattering angle. (b) The same ratio plotted vs E_e, the energy of the electron ejected in a binary collision between the proton and a free electron. Other data points, plotted vs photoelectron energy, are from Ref. 9 (open triangles), Ref. 10 (filled squares), Ref. 1 (filled circles), and Ref. 11 (filled triangles). Theoretical curves for photoionization are from Ref. 6 (dash-dot), Ref. 4 (continuous), and Ref. 5 (dashed).

The difference between values of R for charged-particle impact and photoionization shows clearly that R depends on more than the energy of the fast electron. The possibility must be considered that, in the charged-particle case, double ionization occurs through a double interaction mechanism whereby the proton, in a single pass through the atom, interacts with both electrons. A semiclassical approximation estimate would lead us to expect this process to be weak at 3 MeV and even weaker at 6 MeV. Furthermore, the differential cross sections found here show a sharp discontinuity at 0.55 mrad for double as well as single ionization, which should not be the case for the double interaction process. We conclude that a major contributor to the difference in R between photon and charged-particle cases lies elsewhere. Since a simple shakeoff picture would not lead one to expect different values of R, the importance of correlation contributions is made evident on the basis of a comparison of experimental data from the two experiments alone. We note that a similar, though not so marked, difference was found by Horsdal-Pedersen and Larsen[19] for ionization by capture.

One possible reason for this disagreement can be identified qualitatively. In the photoionization case, q and E_e are approximately related by $E_e = q^2/2m$, where m is the electron mass. (The energy of the electron seen in the laboratory will be lower than E_e by the appropriate binding energy of He.) Thus for large E_e, only high momentum components in the initial wave function for the relative motion of the fast electron and the He^+ system are sampled. In the hard collision case, the large momentum of the fast electron comes mainly from the projectile, and the recoil momentum q remains small, of the order of the average momentum present in the target wave function. Thus all momentum components in the initial He wave function can participate more or less equally in the process. As discussed by Åberg,[2] the photon and charged-particle ionization processes would be expected to give the same value of R only for the same value of q. This is not the comparison allowed by the present data. The relative constancy of R with E_e in our case may result from the fact that the participating momentum sampled in the He wave function does not vary with E_e here, whereas it does in the photoionization case.

In conclusion, we have shown that the ratio of double to single ionization of He attending the sudden removal of a primary electron is lower when this electron is removed by a hard charged-particle impact than when an electron with the same energy is removed by photoionization. It appears that calculations of this ratio for the charged-particle case could be performed with the same formalisms previously employed[4-6] for the photoionization case but such calculations, to our knowledge, have not yet been done. When allied with such a calculation, the present results should serve as an additional probe of correlations in the He wave function, sensitive to a different region of momentum space from that probed by the photoionization experiments.

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