Observation of Electron-Electron Scattering in Electron Capture by Fast Protons from He

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The angular distribution of electrons ejected from He with about the projectile velocity in coincidence with the capture of the other electron by the projectile in 1-MeV proton-He collisions has been measured. The signature of the proton-electron-electron scattering leading to transfer ionization has been observed for the first time as a peak at about 90° in the angular distribution of the ejected electrons. The effect is in qualitative agreement with theoretical predictions.

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Considerable experimental and theoretical effort has been devoted recently to study the intriguing details of atomic collision processes involving the correlated motion of two active electrons. One of the conceptually simplest of these processes is electron capture from He by a fast proton through projectile-electron-electron (p-e-e) scattering. In this process the captured electron first collides with the proton and then scatters into a bound state of the projectile through a second collision with the other target electron, which is ionized due to this scattering. The simultaneous capture and ionization of two target electrons is called transfer ionization (TI) and can occur also through two independent interactions between the projectile and two target electrons. The p-e-e scattering mechanism leading to TI is very similar to the process of electron capture through nuclear double scattering. In that process, first discussed by Thomas[1] in classical terms, the second scattering of the captured electron occurs on the target nucleus. In the quantum-mechanical descriptions[2,3] these double-scattering processes are represented by the second-order terms in the Born expansion. At very high collision velocities, where capture cannot be facilitated by the high-momentum components of the bound states, these double-scattering processes are the dominant mechanisms of electron capture.

The experimental signature of the nuclear double-scattering mechanism is a sharp peak at 0.47 mrad in the angular differential scattering cross section of the charge-changed projectiles, reflecting the fixed kinematics of the first collision of the projectile with the target electron. This signature has been found[4] in p-He, and more clearly in p-H collisions.[5] Similarly, the p-e-e scattering should result in a peak at 0.55 mrad in the angular differential scattering cross section of charge-changed projectiles, which produce He^{2+}. Recently Horsdal, Jensen, and Nielson[6] found a peak at around 0.55 mrad in the ratio of the differential scattering cross sections of charge-changed 0.3–0.7-MeV protons producing He^{2+} and He^{+}, respectively. This result could, however, be described[7] as simultaneous capture and ionization of independent electrons (i.e., without including the electron-electron interaction in the scattering amplitude).

Briggs and Taulbjerg[3] suggested that a signature of the p-e-e-scattering–mediated capture in p-He collisions would be a peak at $v_e = v_p$ (electron velocity equals the projectile velocity) in the energy spectrum of electrons ejected at 90°, or correspondingly a peak at 90° in the angular distribution of $v_e = v_p$ electrons ejected simultaneously with the capture of the other electron by the proton. More recently, Ishihara and McGuire[8] arrived at similar results and pointed out that the p-e-e interaction produces a kinematic ridge in the energy-angular distribution of the electrons ejected in the transfer ionization of He by fast protons. This ridge is due to the overall energy and momentum conservation in a TI process, where there is no momentum transfer to the target nucleus.[8] Therefore, any number of interactions between the projectile, the electrons, and the target nucleus, which result in TI without momentum transfer to the target nucleus can contribute to this ridge, which in the angle-energy plane goes through the (90°, $\frac{1}{2} m_e v_p^2 + \epsilon_i - \epsilon_f$) point, where m_e is the electron mass and, ϵ_i and ϵ_f are the initial and final binding energies.[3,8] Among these interactions the p-e-e scattering can be described in lowest (namely, second) order, and can be expected to give the dominant contribution to that ridge.

From theoretical calculations[3,8] one does not expect a peak in the energy spectrum of electrons ejected at $\sim 90°$ except at very high energies (≥ 5 MeV), where the cross section is prohibitively low (10^{-32} cm^2/eV sr). In an experiment[9] performed with 300-keV protons the effect indeed could not be identified in the energy spectrum of the electrons ejected at 90°. In contrast, the angular distribution of the ejected $v_e \sim v_p$ electrons should clearly peak[3,8] at $\sim 90°$ at projectile energies below 5 MeV, where experimental studies could still be feasible. At these projectile energies, however, the main contribution to the TI cross section comes from a process where simultaneous capture and ionization can be described without including the electron-electron interaction in the scattering amplitude. In this process, which we call uncorrelated TI, the capture occurs due to the momentum components of the bound electrons matching the projectile velocity, and the target nucleus gets the momentum released by the capture. The second electron is ionized by the projectile in a binary-encounter collision. The cross section of this process can be approximated by the product of the probabilities calculated from first-order amplitudes. Consequently, the energy and angular distribution of electrons ejected in this process should give a binary-encounter ridge at about 60° for $v_e \sim v_p$ electrons and follow the energy and angular distribution of the electrons emitted in single ionization.[10] Furthermore, as the first-order contribution increases faster with decreasing projectile velocity than the higher-order contributions, it can mask the signature of the latter in the differential cross section as the projectile energy decreases. Therefore, one has to find a compromise between the feasibility of the experiment and the significance of the higher-order contributions.

In this Letter we report on the measurement of the angular distribution of electrons emitted at fixed energies simultaneously with the capture of the other electron from He by 1-MeV protons. At 600-eV electron energy the p-e-e scattering ridge is expected[3,8] to give a peak in the angular distribution at $\sim 90°$, while the binary-encounter ridge is expected to give a peak at $\sim 60°$, according to the above discussed relations.

The essential parts of the experimental setup are shown in Fig. 1. The proton beam from the 2-MV van de Graaff accelerator at the Manne Siegbahn Institute was collimated to 0.67 mrad and cleaned from H^0 contamination after the second slit (SL2) in an electrostatic cleaner at ~ 50 cm in front of the effusion-gas target (GT) made out of a 0.8-mm-diam hypodermic needle. A second electrostatic deflector at ~ 20 cm behind the target separated the protons (collected in a Faraday cup) from the neutral H atoms, counted by a ceramic channel electron multiplier (CEM). Five turbomolecular pumps maintained 4×10^{-7} mbar operating pressure outside the 30-mm-diam first stage of the differential pumping system, and produced 4×10^{-8} mbar pressure in the chamber without the target gas load. A cylindrical-mirror electron analyzer (CMA) at 90° with respect to the beam was employed to measure the angular distribution of electrons emitted in the angular range of 47.5°-137.5°. A resistive-anode-multichannel-plate (MCP) position-sensitive detector was used to detect the electrons at ~ 11 mm behind the exit slit, positioned at the focal point on the spectrometer axis.

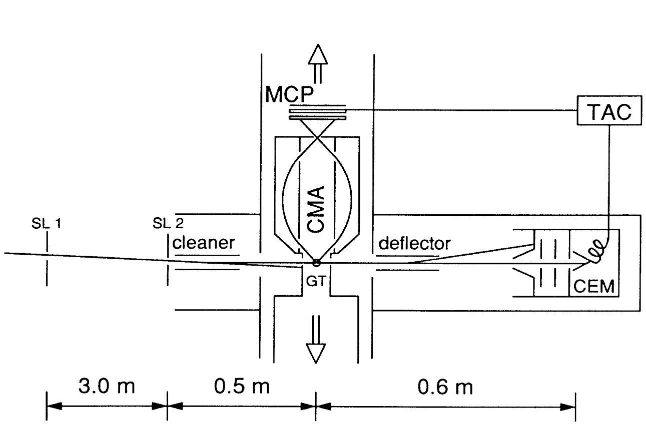

FIG. 1. Schematic of the experimental setup (see also text).

Fast timing signals from the back of the second MCP and from the particle detector CEM were used as start and stop signals for a time-to-amplitude converter (TAC). The time resolution of the total system was 6 ns. Signals from the electron position, the voltage on the electron analyzer, and the time-proportional signal from the TAC were recorded in list mode. The total number of electrons, H atoms, and the total accumulated charge were recorded simultaneously to monitor the long-time stability during the long (~ 120 h for He) measurement. For a typical beam current of 15 nA on He, the H^0 count rate was $\sim 1.5 \times 10^4$ s^{-1}, the count rate for 600-eV electrons was $\sim 4 \times 10^2$ s^{-1}, and the true coincidence rate was $\sim 1 \times 10^{-2}$ s^{-1}. Using the total p-He capture cross section[11] we estimated the He target thickness to be $\sim 4 \times 10^{13}$ atoms/cm^2. The H^0 produced in the residual gas was $\sim 5\%$ of that produced in the He target gas.

Electrons with a given kinetic energy (determined by the analyzer voltage) emitted at different angles into the acceptance cone of the analyzer are imaged to different points within a ring on the MCP detector. The exit slit of the electron analyzer was adjusted for 5% energy resolution, which gave a reasonable compromise of resolution versus transmission. In the off-line sorting of the events, 36 angular segments were established on the position-sensitive detector, which transform into electron-emission-angle regions through a simple geometrical transformation. The number of real coincidences in each angular region were calculated as the difference of the number of events in the time window of real coincidences and those in an equivalent time window of random coincidences.

The experimental setup has been calibrated by measuring the angular distribution of KLL Auger electrons of Ne emitted after an electron has been captured from its K shell by 1-MeV proton projectiles. Setting the electron analyzer on the unresolved K-$L_{23}L_{23}$ and K-L_1L_{23} lines of Ne, and measuring the electrons in coincidence with the H^0, the measured angular distribution of these isotropic lines can be used to measure the angular dependence of the efficiency of the electron detection system. A slow variation (up to 15%) of the efficiency has been found and corrected for in the angular-distribution measurements. The Ne KLL Auger-electron data were also used to establish the absolute scale of the TI cross sections. To achieve this, the coincidence efficiency of the system was determined by using the experimental value[12] of the ratio of Ne K-shell to total capture cross sections, and the ratio of coincident Ne KLL Auger electrons and detected H atoms in our mea-

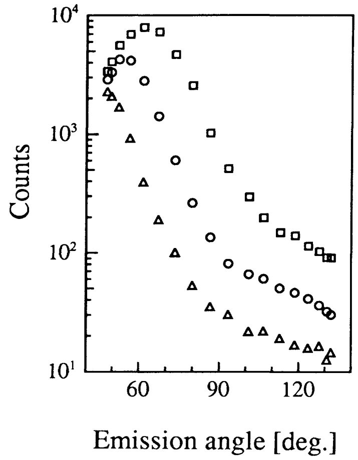

FIG. 2. Angular distributions of electron emission at 300 eV (□), 600 eV (○), and 900 eV (△) following ionization of He by 1-MeV proton impact.

surement. Using this coincidence efficiency and the total capture cross sections,[11,12] the absolute value of the double-differential cross section of electron ejection in TL can be determined from the measured ratio of the coincident electrons and the detected H atoms.

The absolute value of the measured TI cross sections could, in principle, be influenced by an angular-independent contribution from K capture followed by Auger-electron emission from residual gas impurities (e.g., O, N). The selected electron energies, however, are far from Auger lines of possible contaminants and we also verified experimentally that this background is negligible by running the measurements on the residual gas.

In Fig. 2 the angular distributions of electrons from ionization obtained from the random coincidences are shown. The spectra are dominated by the binary-encounter peaks appearing at different angles for the electron energies of 300, 600, and 900 eV. The measured double-differential TI cross sections for Ne and He by 1-MeV protons are shown in Fig. 3. The error bars show only the statistical errors in the measurement, and do not include the errors in the cross sections used to obtain the absolute scale for the data. In neon, where the contribution of the p-e-e scattering to TI is expected to be insignificant, the angular dependence of the measured differential cross section, indeed, does not show any indication of enhancement at 90°. The He data, however, clearly show a peak at ~90°. They sit on a "background," which shows an indication of a maximum at about 60° and smoothly decreases with increasing angle similarly to the dependence in Fig. 2. The total TI cross section is predominantly determined by this previously described uncorrelated capture and ionization process even in proton-He collisions. As the p-e-e scattering does not contribute significantly to the TI cross section in proton-Ne collisions, we can assume that the cross section for uncorrelated TI in proton-He collisions has the same angular dependence as in Ne. The dashed curves in Fig. 3 are drawn by taking a smoothed variation of the cross section from Ne for the uncorrelated process and normalizing it to the He data. We interpret the increase above the dashed curve at ~90° in the He data as electrons from the p-e-e scattering process. The solid curve in Fig. 3 shows in absolute scale the cross section of the p-e-e scattering calculated according to the Briggs and Taulbjerg (BT) formula.[3] The position and the shape of the peak in the calculated cross section are in good qualitative agreement with the measured angular distribution. A similar formula obtained by Ishihara and McGuire[7] (IM) also gives a peak in the angular dependence of the cross section at the same position and with similar shape, but the absolute value of the cross section is higher by about an order of magnitude than the BT results.[3] For an absolute comparison between experiment and theory the theoretical cross sections could be added to the cross section of the uncorrelated process (dashed curve in Fig. 3), if one assumes that the two contributions add incoherently. This gives that the cross sections calculated according to the BT formula[3] are about a factor of 2 higher than the experimental data at ~90°. This discrepancy, however, cannot be considered serious due to the approximations applied.[13] The comparison clearly

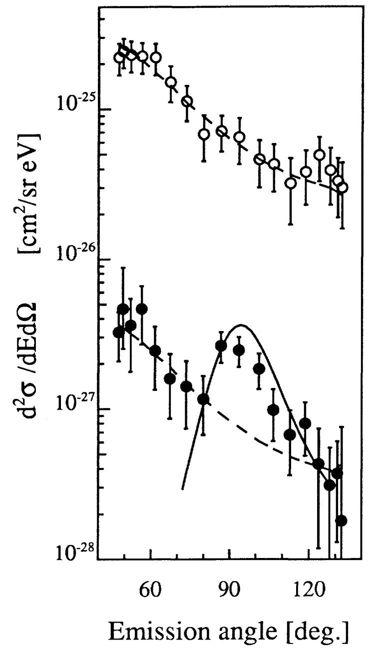

FIG. 3. Double-differential cross section of electron emission at 600 eV following transfer ionization of Ne (○) and He (●) by 1-MeV proton impact. The dashed curves are smooth lines (see text) representing the contribution of the uncorrelated process. The solid curve is the cross section of the p-e-e scattering calculated according to Briggs and Taulbjer (Ref. 3).

supports the interpretation that the observed electrons are emitted from the p-e-e scattering process. The experiment has also been tried at 300- and 900-eV electron energies. At 900 eV the TI cross section was too small to be measured. At 300 eV, the random rate increases due to the higher rate of ionization electrons, so the data are statistically less significant than at 600 eV. Still a clear enhancement was found in the angular distribution at about 110° observation angle, which agrees well with position of the ridge in the calculation of Ishihara and McGuire.[7] The data indicate, however, that the intensity on the ridge decreases relative to the contribution from the independent electron process as the electron energy deviates from 600 eV.

In conclusion, we have been able to identify unambiguously a peak at 90% in the angular distribution of $v_e \sim v_p$ electrons ejected in coincidence with the capture of the other electron by the projection in 1-MeV proton-He collisions. The appearance of this peak can be attributed to the p-e-e scattering, i.e., dynamic electron-electron interaction mediating electron capture in fast p-He collisions

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