VOLUME 86, NUMBER 11 PHYSICAL REVIEW LETTERS 12 MARCH 2001

Strong Correlations in the He Ground State Momentum Wave Function Observed in the Fully Differential Momentum Distributions for the p + He Transfer Ionization Process

V. Mergel,[1,*] R. Dörner,[1,2] Kh. Khayyat,[1] M. Achler,[1] T. Weber,[1] O. Jagutzki,[1] H. J. Lüdde,[3]
C. L. Cocke,[4] and H. Schmidt-Böcking[1]

[1]*Institut für Kernphysik der Universität Frankfurt, August-Euler-Strasse 6, D-60486 Frankfurt, Germany*
[2]*Fakultät für Physik, Universität Freiburg, Herrmann-Herder-Strasse 3, D-79104 Freiburg, Germany*
[3]*Institut für Theoretische Physik der Universität Frankfurt, Robert-Mayer-Strasse 8, D-60054 Frankfurt, Germany*
[4]*Department of Physics, Kansas State University, Manhattan, Kansas 66506*

(Received 23 June 2000)

The four-particle process of proton-helium transfer ionization has been studied using cold target recoil ion momentum spectroscopy to measure the momenta of all three particles in the final state. Most of the electrons are emitted in the H^0 scattering plane and in the backward direction. The final state momentum distributions show discrete structures very different from those expected for uncorrelated capture and ionization. The measured momentum pattern is interpreted to be due to a new transfer ionization reaction channel which results from strong correlations in the initial He ground state momentum wave function.

DOI: 10.1103/PhysRevLett.86.2257 PACS numbers: 34.70.+e, 34.50.Fa, 39.90.+d

The dynamics of entangled many-body Coulomb systems is still one of the most fundamental challenges in physics. Even the simplest test case, the dynamics of the three-body Coulomb problem, has yet to be fully understood. Since the helium atom is the simplest many-electron system, its investigation has attracted particular interest from both the experimental and the theoretical sides [1,2].

We present here a systematic investigation of the four-particle collision process of $p + \mathrm{He} \rightarrow \mathrm{H}^0 + \mathrm{He}^{2+} + e^-$ transfer ionization (TI), where the momenta of all particles in the final state have been determined in coincidence with high resolution. One target electron is transferred to a projectile bound state (predominantly the $1s$ state), while the second one is emitted to the continuum.

The electron capture can proceed via different reaction channels: (i) electron-electron Thomas (EET) [3–5], (ii) nucleus-electron Thomas (NET), and (iii) kinematical capture (K). In order to accomplish TI, the second electron must also be ionized. While the EET capture process does this automatically, the last two capture processes must be accompanied by an additional process such as shakeoff (K-SO or NET-SO) or an independent ionization of the second electron by the projectile (K-TS2 or NET-TS2). In the subsequent discussion, we will refer to these as two-step mechanisms for TI.

Our study was stimulated by the systematic work of Horsdal *et al.* [6] on TI processes for p on He. These authors found a pronounced peak at about 6×10^{-4} rad in the H^0-scattering-angle-dependent ratio of TI to pure capture. The peak maximum increased with projectile energy E_p and reached about 25% at 1 MeV proton impact energy. They interpreted this finding to indicate a possible large contribution from the EET process. However, Olson [7] and Gayet and Salin [8] later showed, by classical and quantum mechanical calculations within the independent electron approximation, that two-step processes can also produce such peak structures. Each of the processes listed above will lead to the population of well-defined parts of the final-state momentum space, as outlined below. By measuring the momenta of all fragments, we can therefore clearly distinguish the different processes. Based on our measured final state momentum distributions, we will show that neither EET nor two-step processes are responsible for the observed peak in the ratio. Our data show strong evidence for a new TI reaction channel, which we term c-K-TI (c stands for strong correlation), mediated by e-e correlation in the initial momentum wave function.

The experiment was performed by measuring the three-dimensional momentum vector of the recoiling He^{2+} ion in coincidence with the polar and azimuthal scattering angle of the projectile. The momentum vector of the emitted electron was then calculated from momentum conservation (see [5]). The experimental momentum uncertainty was about 0.2 a.u. Details on the experiment can be found in [5].

We first discuss the relative dependence of the measured cross sections on E_p and the H^0 transverse momenta to show that two-step processes cannot explain important features of the data. In Fig. 1, the singly differential charge transfer and transfer-ionization cross sections are shown as functions of the H^0 transverse momenta. The charge-transfer cross sections [Fig. 1(a)] show a large hump for $p_\perp$ corresponding to H^0 scattering angles less than 5.5×10^{-4} rad (i.e., the region on the left side of the solid line) and a weaker dependence on the H^0 transverse momentum for scattering angles above 5.5×10^{-4} rad. The transverse deflection of the projectile in the region of the hump is created by transverse momentum transfer exchange through the captured electron only (Compton profile) (see [9]). For these small deflection angles, the proton passes the He atom at very large nuclear impact parameters (typically $\approx$1 a.u.) and the nuclear deflection is thus negligibly small. This is similar to the small

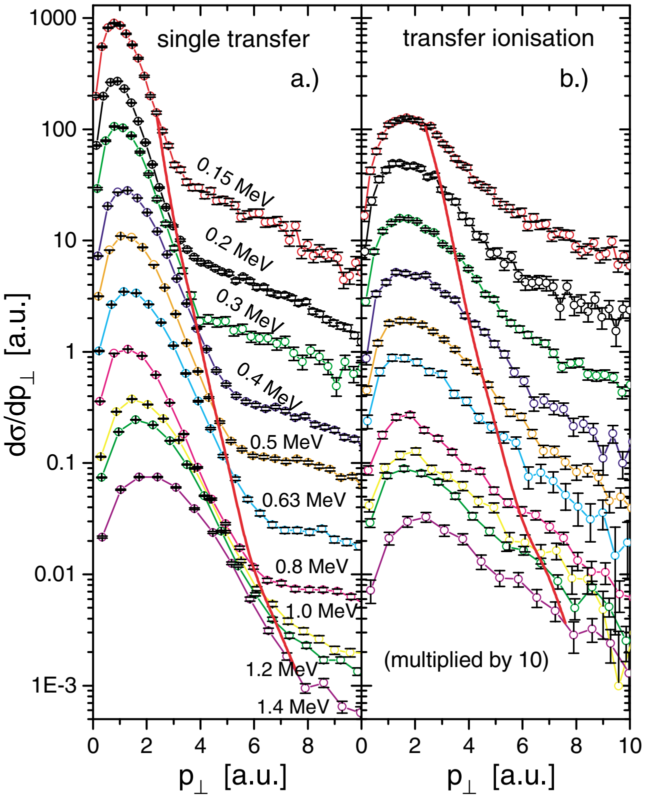

FIG. 1 (color). Differential cross sections for (a) the $p + \mathrm{He} \rightarrow \mathrm{H}^0 + \mathrm{He}^{1+}$ $(1s)$ single electron transfer processes and (b) differential cross sections for the TI process as a function of the H^0 transverse momentum for different proton impact energies. The solid curve separates the small and the large angle scattering angular regimes (left side: below 0.55 mrad; right side: above 0.55 mrad).

angle scattering for ionization where, up to an angle of 0.55 mrad, the projectile is mainly scattered from the electron [10].

A similar feature is seen for the transfer-ionization channel, although the hump is broader. The measured ratio of the total cross section for transfer ionization to that for capture is nearly independent of the incoming proton energy E_p and is approximately 2.5% for all E_p (150 to 500 keV). Above 500 keV, the ratio increases and reaches about 4% at an E_p of 1.4 MeV. If TI resulted from a process in which the capture and ionization occurred in two independent steps, the transfer-ionization probability at a given transverse momentum would be the product of a capture probability times an ionization probability P(I). Therefore, the ratio of the total TI cross section to the total single-capture (SC) cross section, as well as the corresponding scattering-angle-dependent ratio, should drop as $1/E_p$ (for K-TS2 or NET-TS2) or remain constant (for K-SO or NET-SO), following the energy dependence of P(I). These arguments are strongly supported by previous work on the ratio of double to single ionization in both differential and total cross section measurements. The double ionization in this energy regime is known to be dominated by a two-step (TS2) mechanism. The measured ratio decreases with increasing proton energy [11,12]. In contrast to this result, the TI/SC total cross section ratio in Fig. 1 does not decrease with increasing projectile energy, but instead actually increases above 500 keV. The same is true for the ratio of scattering-angle-dependent probabilities. We obtain [5] the same scattering-angle dependence and peak structure as were obtained by Horsdal and co-workers [6]. Again the peak value increases with increasing E_p. Thus, from the data in Fig. 1, we can draw two conclusions: (i) At angles below 0.55 mrad, the data are not consistent with a two-step process for TI; (ii) at these small angles, nuclear momentum exchange plays a minor role.

To further elucidate the behavior of the c-K-TI channel, we first discuss at which locations in momentum space the different TI channels are expected and then compare these expectations with the measured data. In the single capture process (K process) those electrons are capture, whose initial state velocity matches the projectile velocity. It can be shown [13], from energy and momentum conservation, that the He^{1+} recoil ion will receive a longitudinal momentum transfer in the backward direction of $mv_P/2 - Q/v_P$, where v_P is the projectile velocity, and Q is the difference in electronic energies in the initial and final states. This backward momentum is the characteristic signature of kinematical capture processes. The transverse-momentum transfer to the He^{1+} recoil must exactly balance that given to the projectile. For the transfer ionization case, it is expected [14] that the additional ionized electron (2) has a rather small kinetic energy due to either a shakeoff process or due to ionization by an independent encounter with the proton [8] [distant collision between proton and electron (2)]. If the continuum electron leaves with a small transverse momentum, the transverse momentum of the recoil must balance that received by the projectile; if the continuum electron is ejected by a hard collision between projectile and electron (2), the recoil transverse momentum will be small and the projectile transverse momentum is balanced by that of electron (2). For the EET process, the target nucleus is only a spectator and receives no momentum transfer at all. If we take k_x to be in the direction of the H^0 transverse momentum $P_\perp(\mathrm{H}^0)$, k_y to be the direction perpendicular to the H^0 scattering plane, and k_z to be the beam direction (Mergel [5]), the different TI channels are thus expected to produce mean recoil momenta centered about the following: For EET, $(k_x, k_y, k_z) = (0, 0, 0)$; for two-step processes (including NET-TI) with the transverse momentum balanced by the recoil, $[-P_\perp(\mathrm{H}^0), 0, -mv_P/2]$; for two-step processes with the transverse momentum balanced by electron (2), $[0, 0, -mv_P/2]$.

In Fig. 2 we show the projections of the three-dimensional momentum distributions of the He^{2+} recoil-ion [2(a) and 2(b)] and those of the corresponding electron (2) [2(c)–2(f)], projected onto the H^0 scattering plane for different H^0 scattering angles θ_p and for

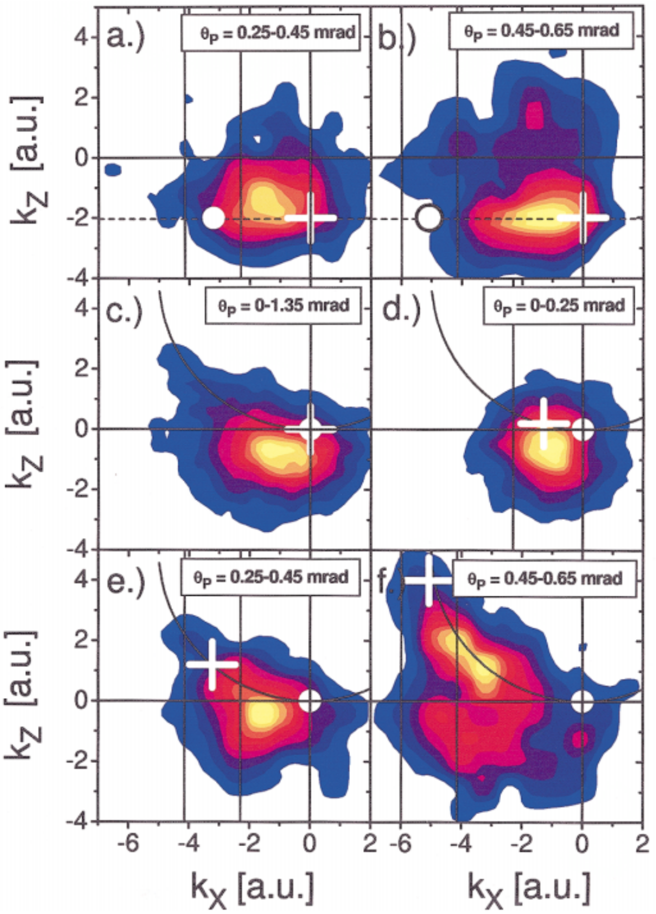

FIG. 2 (color). (a),(b) Recoil ion and (c)–(f) electron momentum distributions projected onto the H^0 projectile scattering plane for different H^0 scattering angles θ_p. k_z is the direction of the incoming projectile momentum, k_x is the direction of the scattered H^0 transverse momentum, and k_y is the transverse momentum perpendicular to the scattering plane. The lines and symbols are explained in the text.

$E_P = 630$ keV. Figure 2(c) shows a contour plot of the electron distribution integrated over all θ_P, thus showing the doubly differential cross section $d\sigma/(dk_x dk_z)$. The vertical solid lines (negative k_x and $\parallel k_z$) show the transverse recoil and electron momenta, respectively, corresponding to the H^0 transverse momentum window, i.e., $k_x = -q_x = -M_P v_P \theta_P$.

From Figs. 2(a)–2(f), it is evident that the recoil and electron momentum spectra always show localized peak structures with nonzero momenta. This is indeed surprising as these spectra represent the projection from all k_y components (i.e., all azimuthal angles with respect to the H^0 scattering plane). This shows that electron (2) and the recoil ion are both emitted within a narrow cone (<1 a.u.) in the H^0 scattering plane. The mean longitudinal recoil momenta are located close to $-mv_p/2$, indicating that K-TI and NET-TI are the dominating processes for all angles and that the EET contribution is negligible at these angles and impact energy (contrary to the explanation given by Horsdal *et al.* [6]). NET-TI can also be excluded since no cross section is found at a recoil momentum of $(k_x, k_y, k_z) = (-k\perp(H^0), 0, -mv_P/2)$.

If the hydrogen atom reaches a chosen scattering angle through two uncorrelated interactions of the proton with the He nucleus and with target electron (2) (two-step process), the transverse-momentum transfers to the He nucleus or electron will be representative of a single interaction with only one of these target constituents at a time, with the other acting as a spectator. This result is known in studies of multiple scattering of charged particles passing through matter. We established it for this case by performing classical trajectory Monte Carlo calculations of the double scattering of protons from both the He nucleus and an electron, and identifying which kind of events contributed to scattering at a chosen final angle. The result shows that the overwhelming contributors at any final angle are events in which a hard scattering from the nucleus is accompanied by a soft scattering from the electron or vice versa [15].

The dashed line [Figs. 2(a) and 2(b)] at $k_z = -2$ a.u. and the white bullets represent the predicted k_z and k_x values for the recoil ion if the He recoil nucleus alone compensates the momentum of the transferred electron (1) and electron (2) acts as a spectator. In this case, electron (2) is emitted to the continuum with nearly zero kinetic energy. The circular solid line in Figs. 2(c)–2(f) and the crosses represent the predicted locations of the electron momentum if the proton undergoes a close binary collision with electron (2), and the He recoil nucleus acts as a spectator [see corresponding recoil positions in Figs. 2(a) and 2(b)]. Figures 2(b) and 2(f) represent the cross section for $\theta_P \in [0.45, 0.65]$ mrad, which is centered on the maximum angle caused by a proton scattered from an electron at rest and equal to the critical angle for the *e*-*e* Thomas mechanism (both ideally 0.55 mrad).

At all H^0 scattering angles <0.65 mrad for all E_p investigated (see [5]), the measured transverse momenta never coincide with the expected locations for the two-step processes. On the contrary, the recoil and electron transverse momenta are found between the expected locations, providing that these TI events cannot be created by uncorrelated double scattering of the proton on the nucleus and on the electron (2). Thus, the peaking in the ratio of TI-to-capture probabilities observed in [6] cannot be due to EET nor to the two-step processes. Furthermore, we find that the mean momentum vectors of both the electron and the He^{2+} recoil ion are always lying in the H^0 scattering plane (see Fig. 2). This observation is again in conflict with the assumption of two-step processes. The transverse-momentum transfer in two independent scattering events would be randomly oriented with respect to the H^0 scattering plane.

To explain the observed recoil and electron transverse-momentum locations, we believe that only a previously unidentified, correlated TI process (c-K-TI) can create the

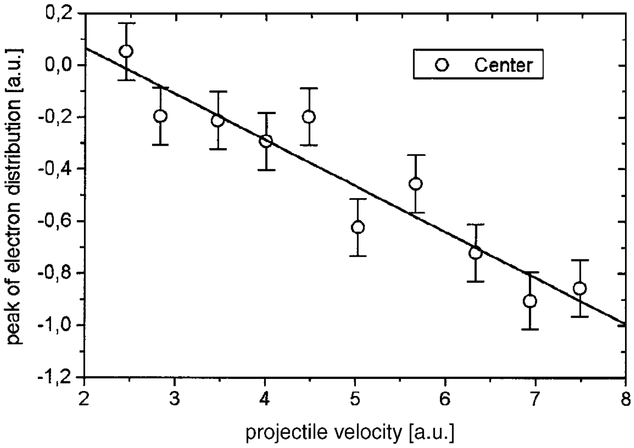

FIG. 3. Longitudinal electron momentum component k_z for electron (2) in the c-K-TI process as a function of proton impact velocity. The solid line is to guide the eyes.

observed pattern. Since in this process only a very small momentum is transferred from the proton to the He system, we believe that the correlated momenta in the initial He ground state play the crucial role. The process seems to occur only when the three particles in the He ground state are in a correlated momentum state. Thus, this process may provide an observation window through which correlation in the initial state momentum wave function can be directly revealed through the final state momentum distributions, very different from the traditional way of comparing probabilities.

The conclusions presented above are strongly supported by another feature seen in our data. As shown in Fig. 3, the longitudinal components of the momentum of electron (2) for very small H^0 transverse momenta show an increasing backward emission with increasing v_P. Again no two-step process would ever produce backward-emitted electrons. To our knowledge, this is the first time in ion-atom collisions that the majority of emitted electrons are observed to go into the backward direction. In a c-K-TI process due to initial-state correlation, however, the observed trend can easily be understood: The capture process picks out, by velocity matching, components of the initial-state wave function for which electron (1) has large forward directed momenta equal (in atomic units) to v_P. In a correlated initial state, high forward momenta of one electron will correspond to high backward-directed momenta of the second electron, in agreement with the data in Fig. 3.

We conclude the following from the different data discussed: (i) the locations of the recoil and electron transverse momenta, (ii) the discrete momentum sharing between recoil and electron, (iii) the confinement of recoil and electron momentum vectors in the H^0 scattering plane, and (iv) the backward electron emission that the TI contributions here observed can never be explained by any sequence of uncorrelated scattering processes. To the best of our knowledge, only initial-state correlation in the three-particle He ground-state wave function can be responsible for these observations. Preliminary results of numerical calculations by J. Berakdar [16] indeed show the importance of initial-state correlation for the TI process.

This work was supported by DFG, BMBF, GSI, and EU. R. D. acknowledges support by the Heisenberg Programm (DFG) and the Adolf Messer Stiftungs-Preis, Kh. K. by the DAAD, T. W. by the Graduiertenförderung des Landes Hessen, and V. M. by the Studienstiftung des Deutschen Volkes. We thank ROENTDEK for preparation of the position sensitive detectors and other technical equipment. We thank our colleagues and friends J. Berakdar, J. Briggs, J. Burgdörfer, R. Dreizler, J. Feagin, W. Greiner, S. Hagmann, E. Horsdal-Pedersen, S. Manson, H. Schmidt, H. Cederquist, J. McGuire, R. Moshammer, R. E. Olson, J. Reading, J. M. Rost, V. Schmidt, R. Schuch, and J. Ullrich for many helpful discussions and disputes.

---

*Electronic address: schmidtb@hsb.uni-frankfurt.de

[1] J. Briggs and V. Schmidt, J. Phys. **33**, R1 (2000).
[2] A. Lahmam-Bennani *et al.,* Phys. Rev. A **59**, 3548 (1999).
[3] J. S. Briggs and K. Taulbjerg, J. Phys. B **12**, 2565–2573 (1979).
[4] J. Palinkas *et al.,* Phys. Rev. Lett. **63**, 2464–2467 (1989).
[5] V. Mergel, Ph.D. thesis, Universität Frankfurt (ISBN 3-8265-2067-X), Shaker Verlag, 1996.
[6] E. Horsdal *et al.,* Phys. Rev. Lett. **57**, 1414 (1986).
[7] R. E. Olson *et al.,* Phys. Rev. A **40**, 2843 (1989).
[8] R. Gayet and A. Salin, Nucl. Instrum. Methods Phys. Res., Sect. B **56/57**, 82–85 (1991).
[9] Dž. Belkić and R. Gayet, J. Phys. B **10**, 1911–1921 (1977).
[10] E. Y. Kamber *et al.,* Phys. Rev. Lett. **60**, 2026 (1988).
[11] L. H. Andersen *et al.,* Phys. Rev. Lett. **57**, 2147 (1986).
[12] F. G. Kristensen and E. Horsdal-Pedersen, J. Phys. B **23**, 4129 (1990).
[13] R. Dörner *et al.,* Phys. Rep. **330**, 96–192 (2000).
[14] J. H. McGuire, *Electron Correlation Dynamics in Atomic Collisions* (Cambridge University, Cambridge, England, 1997).
[15] W. R. DeHaven *et al.,* Phys. Rev. A **57**, 292 (1998).
[16] J. Berakdar (private communication).