01 Jan 1989

Three-body Interactions In Proton-helium Angular Scattering

R. Dörner

J. Ullrich

H. Schmidt-Böcking

Ronald E. Olson
Missouri University of Science and Technology, olson@mst.edu

Recommended Citation

R. Dörner et al., "Three-body Interactions In Proton-helium Angular Scattering," *Physical Review Letters*, vol. 63, no. 2, pp. 147 - 150, American Physical Society, Jan 1989.
The definitive version is available at https://doi.org/10.1103/PhysRevLett.63.147

Three-Body Interactions in Proton-Helium Angular Scattering

R. Dörner, J. Ullrich, and H. Schmidt-Böcking
Institut für Kernphysik, Universität Frankfurt, D-6000 Frankfurt am Main 90, Federal Republic of Germany

R. E. Olson
Department of Physics, University of Missouri-Rolla, Rolla, Missouri 65401

(Received 23 February 1989)

$H^+ + He$ scattering at 0.5 MeV has been investigated using a coincidence technique that completely determines the three-body transverse momentum exchange in single-ionization collisions. Three scattering regions could be distinctly recognized that are dominated by proton–helium-nucleus, proton-electron, or electron–helium-nucleus interactions. Calculations and the experimental data show that the coupling between the electronic and nuclear degrees of freedom is required to understand the dynamics for more than 97% of the ionizing collisions.

PACS numbers: 34.10.+x, 34.50.Fa

The investigation of single and double ionization of He by swift (MeV/u) singly charged projectiles is of fundamental interest in ion-atom collision physics and has recently attracted extensive experimental and theoretical attention, stimulated by surprising results for antimatter impact.[1] Although highly differential He ionization cross sections have been measured for e^- impact using a coincidence determination of the total momentum of the two outgoing electrons,[2] most experimental studies for heavy-projectile impact have concentrated on total cross sections. These experimental results can be theoretically described by quantum-mechanical[3] and classical[4,5] calculations. Only recently, two experimental studies[6,7] on the projectile scattering distribution for He single and double ionization have been reported and show unexplained structure in the scattering angle dependence.

In this Letter we present the first doubly differential cross sections for 0.5-MeV singly ionizing H^+ on He collisions in a ϑ (the laboratory H^+ scattering angle) regime between 0.1 and 2.0 mrad. The projectile deflection in the plane perpendicular to the beam axis was determined in coincidence with the recoil-ion transverse momentum and charge state. Thus, for the first time the complete three-body transverse momentum exchange between projectile, target nucleus, and electron could experimentally be observed for a heavy-particle collision. Analysis of these data demonstrates that the coupling of electronic and nuclear degrees of motion is extremely important for the description of the collision dynamics. Also, the use of a central potential with a unique correspondence between impact parameter and scattering angle is invalid for a major fraction of ionizing collisions. Our joint experimental and theoretical study clearly shows that the proton scattering cannot be explained by two-body kinematics involving either the projectile–target-nucleus or the projectile–target-electron interactions.

The experimental results are compared to calculations made using the *n*-body classical-trajectory Monte Carlo (*n*-CTMC) approach.[8] Both target electrons are included in three-dimensional calculations that incorporate all interactions except those between the electrons (i.e., the electrons are not correlated). The inclusion of the two electrons in the calculation allows both the projectile and the He nucleus to be properly screened from one another at both small and large internuclear distances. The *n*-CTMC results give a total single-ionization cross section of 3.34×10^{-17} cm^2, slightly lower than the experimental value of $(3.70\pm0.15)\times10^{-17}$ cm^2.[9] The calculated projectile angular differential cross sections are in quantitative agreement with Giese and Horsdal.[6] The *n*-CTMC method explicitly includes the post-collision interactions and the coupling between the electronic and nuclear motions.

The experiments were performed at the 2-MV Van de Graaff accelerator of the Institut für Kernphysik, University of Frankfurt. Only a short description of the experimental setup will be given here. A detailed discussion of the experiment will be presented in a subsequent paper. The proton beam was collimated to a divergence of less than 0.1 mrad over a total collimation length of 5 m. A two-dimensional position-sensitive channel-plate detector with a resolution of less than 200 μm detected the scattered projectiles about 3 m downstream from the target region. The undeflected part of the beam was dumped on a mask of 0.5 mm diam directly in front of the detector.

The recoil-ion transverse momentum (with respect to the beam axis) is measured by a time-of-flight technique[10] using a new spectrometer with a low-temperature (30 K) He target. The extended target region (a cylinder, coaxial to the beam direction of 5 mm diam and a length of 40 mm with incoming and outgoing beam apertures of 1.0 mm diam) was designed to be "free" of electric and magnetic fields. Hence, the recoiling target ions, produced along the beam axis, drift from the axis to the wall of the target cylinder in a time interval Δt inversely proportional to the transverse velocity

$v_{R\perp}$ they obtained in the collision. The recoil ions leave the cylinder through a small aperture ($\Phi = 1$ mm); they are accelerated, charge-state analyzed, and detected by a two-dimensional position-sensitive channel-plate detector. A coincidence between the scattered projectiles and the recoil ions provides, after corrections for inherent flight times in the apparatus and electronic processing times, the flight time Δt of the recoil ion which can be transformed into the transverse velocity, momentum, or energy. Since the target region is extended, the recoil-ion scattering angle ζ is not determined and all ζ between $+25°$ and $155°$ are accepted with the same solid angle. However, only the transverse component of the velocity is detected. Moreover, the apparatus design is such that the scattering plane is determined by the beam axis and the recoil-ion aperture. The target-gas pressure was about 10^{-3} hPa.

The energy transferred to the recoil ion in a two-body collision with the projectile, which is scattered to a deflection angle of 0.1 mrad, is estimated to be 1.3 meV. From this value it becomes obvious that the Boltzmann thermal motion of the target atoms has to be reduced considerably to observe the very small momentum transfers of interest. Therefore, the He target gas was cooled by a cryopump to a temperature of about 30 K, which was measured by Pt resistors.

In order to avoid contact potentials, the cylindrically shaped target cell was constructed out of a single copper block and the recoil-ion aperature was covered on the outside by a copper grid (mesh width: 0.12 mm by 0.12 mm). In succeeding experiments the copper cell was gold-plated to circumvent possible potentials between the Cu basis material and oxides on the surface. Moreover, the outside mesh was removed and the inner surface was completely lined with either a gold or a copper grid in order to have a more "perfect" Faraday cage. Before each experiment the target cell was cleaned in an ultrasonic bath. Identical results were obtained, within statistical error bars, for all three surface-grid combinations. Furthermore, in most cases, any contamination inside the target cell presents itself by a noticeable disturbance in the time-of-flight spectra. From our experimental tests, we estimate that the absolute accuracy of the recoil-ion's energy determination is ± 5 meV.

In Fig. 1(a), the deflection (in mrad) of the protons in a plane perpendicular to the beam axis (x-y plane) is shown for fixed momentum transfer to the singly charged He^+ recoil ion in the x direction of $0.9 \leq |p_{Rx}/p_0| \leq 1.1$ (p_0 is the incoming projectile momentum), which is equivalent to recoil-ion energies between 100 and 150 meV. Zero deflection of the beam is marked by the cross.

Instead of a definite scattering angle of the projectile into the indicated shaded area, expected from a two-body collision between the proton and the He nucleus, a large number of other projectile deflections can be observed. Since the influence of the target thermal motion is negligible for these "high" recoil-ion energies, this broadening of the projectile angular distribution is due to the exchange of transverse momentum with the ejected target electron. Applying momentum conservation, the ejected-electron transverse momentum can be obtained for each collision event from the distance of the detected projectile position to the shaded area. We note that the calculation of the projectile transverse deflection using any central scattering potential would lead to values indicated by the shaded area in the figure.

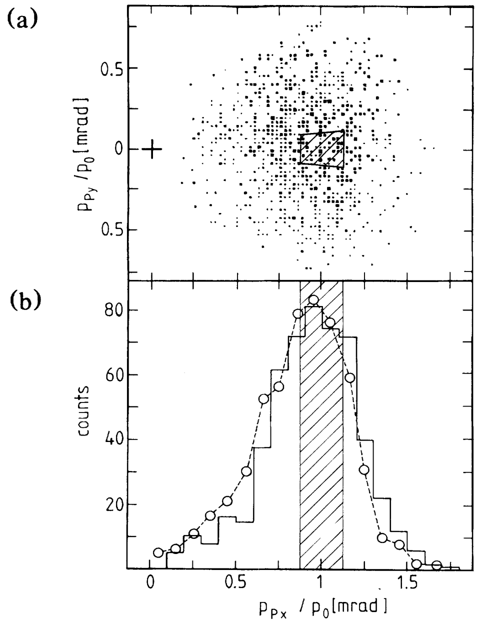

FIG. 1. (a) Projectile deflection in a plane perpendicular to the beam direction for fixed recoil-ion momentum of $0.9 \leq |p_{Rx}/p_0| \leq 1.1$ in 0.5-MeV singly ionizing H^+-He collisions. The shaded area indicates the proton scattering angle expected from a two-body collision with the He nucleus. (b) Projection of the proton scattering in (a) onto the x axis (histogram). Open circles: result of n-CTMC calculations. Shaded area: recoil-ion momentum window.

To allow for a quantitative comparison of the experimental results with n-CTMC calculations, the distribution shown in Fig. 1(a) is projected onto the x axis, Fig. 1(b). Since no absolute experimental data could be obtained in this first measurement, the integral of the distribution is normalized to the theoretical results (open circles). Also indicated in the figure (shaded area) is the projectile momentum range which would correspond to the chosen recoil-ion momentum window for a two-body collision. The width of the measured distribution of about 1.1 mrad is consistent with the maximum possible proton deflection of 0.55 mrad in each direction from a binary encounter with a stationary target electron and is in good agreement with the calculated one. The Comp-

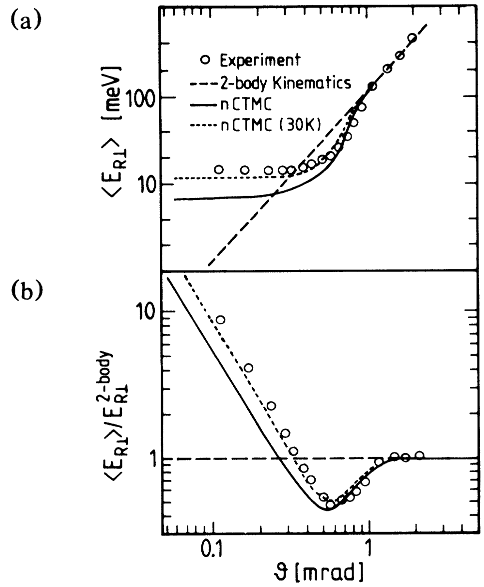

FIG. 2. (a) Mean transverse recoil-ion energy $\langle E_{R\perp}\rangle$ (open circles) in dependence of the projectile scattering angle ϑ for singly ionizing 0.5-MeV H^+-He collisions. Full line: *n*-CTMC calculation. Dotted line: *n*-CTMC results folded with target thermal motion for the experimental target temperature of 30 K. Dashed line: results for a two-body collision between the proton and the He nucleus. (b) Ratio of the recoil-ion transverse energy $\langle E_{R\perp}\rangle$ to that expected in a two-body collision $E_{R\perp}^{\text{two-body}}$. Notation is the same as in (a).

ton profile of the He electron before its ionization gives rise to a further broadening of the proton deflection which is reflected in both the theoretical and experimental results. As an unexpected result, the experimental as well as the theoretical mean momentum transfer to the proton is slightly smaller than that of the recoil ion, indicating that the ionized electron is preferentially ejected away from the recoiling He^+ ion.

In Fig. 2(a) the mean transverse energy transferred to the recoiling target ion is plotted versus the proton laboratory scattering angle ϑ. For a two-body scattering process between the projectile and the He nucleus, as well as for any central scattering potential, both final momenta will be identical which is indicated by the dashed line. In Fig. 2(b) the theoretical and the experimental results are divided by the two-body momentum exchange value to visualize the strong observed deviation. Only for very close collisions $b \lesssim 0.2a_0$ (leading to projectile deflections of more than ~1 mrad), which contribute only 3% to the total cross section, is the proton scattering dominated by the interaction with the He nucleus. Even in this regime, the initial momentum distribution of the He target electron as well as that for the final ionized electron have a measurable influence on the proton trajectory, Fig. 1.

For H^+ deflections smaller than 0.9 mrad, deviations from the expected two-body proton–helium-nucleus scattering is observed. Around the maximum laboratory scattering angle for a proton from a free electron of ~0.55 mrad, the theoretical as well as experimental mean transverse recoil-ion energy is more than a factor of 2 below the two-body value. (To allow for a quantitative comparison of the experimental data with theory at these very small momentum transfers, the theory was folded with the Boltzmann thermal-motion distribution, represented by the dotted line in the figure.)

However, the mean recoil-ion energy does not drop to a value near zero as might have been expected, but saturates at a finite value for small projectile scattering angles. The experimental saturation value of about 15 meV is not determined by the target thermal-motion velocity distribution, which only yields a small contribution of ~4 meV at 30 K. The experimental value has been obtained in three separate experiments with different target-cell-grid combinations so that it is very unlikely to be due to any contact potentials present in the target region. However, the determination of the target-gas temperature may be uncertain by up to +20 K. Since the recoil-ion momentum is much larger than the one transferred to the proton, the three-body momentum transfer is now primarily due to the final-state interaction of the ionized electron with its parent nucleus. The theoretical saturation value for the mean transverse recoil-ion energy of 6.5 meV for "zero-deflection" of the projectile is equivalent to a mean transverse energy of the ionized electron of 47 eV. The mean emitted electron energy, integrated over all emission angles, is calculated in the *n*-CTMC approach to be 56 eV, which is in close agreement with the experimental value of 54 eV reported by Rudd *et al.*[11] Since the mean emission angle is about 65°, this corresponds to a calculated mean transverse electron energy of about 50 eV, which shows that the mean recoil-ion energy is completely compensated by that of the emitted electron. The saturation effect demonstrates the importance of the electron-nucleus interaction in the three-body momentum exchange at projectile scattering angles smaller than 0.3 mrad.

The $H^+ + He$ coincidence spectrum was also calculated for 1-MeV impact. Surprisingly, the saturation energy was not the same as at 0.5 MeV, which would be the case if it primarily reflected the electronic internal momentum distribution before the collision. We find the saturation energy to be ~50% larger at 1 MeV than at 0.5 MeV. The reason being that the calculated mean ionized electron energy increased to 62 eV from 55 eV (0.5 MeV), with the mean ejection angle also increasing to 70° from 65°. The saturation-energy values are primarily determined by the ionized-electron, recoil-ion momentum balance.

We have also calculated the recoil-ion spectra for 0.5-MeV antiproton-He collisions and find measurable differences in the recoil-ion spectra. Notable is that the recoil-ion saturation energy at small projectile scattering angles is ~50% greater for antiprotons than protons. This behavior is largely due to a greater average ionized-electron scattering angle (i.e., closer to 90°) for antiproton versus proton impact on He.

The distinct peak in the ratio of double to total ionization at projectile deflections of about 1.0 mrad in 0.3- to 1.0-MeV proton-He collisions, which has been reported recently by Giese and Horsdal,[6] can be explained on the basis of the results given here. Our *n*-CTMC calculations also place the peak at 1.0 mrad. The structure is due to an uncorrelated double collision between the proton and the two electrons in the double-ionization reaction. A similar phenomenon is known from multiple scattering by screened Coulomb potentials:[12] The ratio between double and single events will always show a peak if the events are uncorrelated. We note that the cross-section ratio is complicated by the fact that the scattering around 1.0 mrad is determined by only small-impact-parameter collisions for single ionization, while all impact parameters contribute for double ionization.

In conclusion, we have applied a new technique to measure the projectile scattering in a plane perpendicular to the beam direction in coincidence with the transverse momentum of singly ionized recoil ions, which allowed a complete experimental determination of the momentum balance between the projectile, the target nucleus, and the ionized electron. *n*-CTMC calculations are found to be in good agreement with the experimental data. We have demonstrated that a central interaction potential is invalid to describe the heavy-particle scattering for a major portion (97%) of ionizing collisions and that the three-body coupling between electronic and nuclear motion is required to understand the collision dynamics. It is surprising that even the most sophisticated coupled-channel quantum-mechanical treatment for the $H^+ + He$ angular scattering[13] does not consistently include the coupling between the electronic and nuclear degrees of motion.

One of the authors (R.E.O.) would like to thank the von Humboldt Foundation for support. The experimental work was supported by the Bundesministerium für Forschung und Technologie (BMFT: 060F/73).

---

[1] L. H. Andersen, P. Hvelplund, H. Knudsen, P. Moller, K. Elsener, K.-G. Rensfelt, and E. Uggerhoj, Phys. Rev. Lett. **57**, 2147–2150 (1986).

[2] H. Erhardt, K. Jung, G. Knoth, and P. Schlemmer, Z. Phys. D **1**, 3 (1986).

[3] J. F. Reading and A. L. Ford, Phys. Rev. Lett. **58**, 543–546 (1987).

[4] S. J. Pfeifer and R. E. Olson, Phys. Lett. **92A**, 175 (1982).

[5] R. E. Olson, T. J. Gay, H. G. Berry, E. B. Hale, and V. D. Irby, Phys. Rev. Lett. **59**, 36 (1987).

[6] J. P. Giese and E. Horsdal, Phys. Rev. Lett. **60**, 2018–2021 (1988).

[7] E. Y. Kamber, C. L. Cocke , S. Cheng, and S. L. Varghese, Phys. Rev. Lett. **60**, 2026–2029 (1988); E. Y. Kamber, C. L. Cocke, S. Cheng, J. H. McGuire, and S. L. Varghese, J. Phys. B **21**, L455–L459 (1988).

[8] R. E. Olson, in *Electronic and Atomic Collisions,* edited by H. B. Gilbody, W. R. Newell, F. H. Read, and A. C. H. Smith (Elsevier, Amsterdam, 1988), pp. 271–285.

[9] M. B. Shah and H. B. Gilbody, J. Phys. B **18**, 899–913 (1985).

[10] J. Ullrich, H. Schmidt-Böcking, and C. Kelbch, Nucl. Instrum. Methods Phys. Res., Sect. A **268**, 216–224 (1988).

[11] M. E. Rudd, Y. K. Kim, D. H. Madison, and J. W. Gallagher, Rev. Mod. Phys. **57**, 965 (1985).

[12] G. Moliere, Z. Naturforsch. **3a**, 78 (1948).

[13] J. F. Reading, A. L. Ford, and X. Fang, Phys. Rev. Lett. **62**, 245 (1989).