01 Oct 2006

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Michael Schulz
Missouri University of Science and Technology, schulz@mst.edu

T. Ferger

Daniel Fischer
Missouri University of Science and Technology, fischerda@mst.edu

R. Moshammer

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/phys_facwork/299

Recommended Citation

M. Schulz et al., "Multiple Scattering Mechanisms in Simultaneous Projectile-Electron and Target-Electron Ejection in H^- + He Collisions," *Physical Review A: Atomic, Molecular, and Optical Physics*, vol. 74, no. 4, pp. 042705-1-042705-6, American Physical Society (APS), Oct 2006.
The definitive version is available at https://doi.org/10.1103/PhysRevA.74.042705

Multiple scattering mechanisms in simultaneous projectile-electron and target-electron ejection in H^-+He collisions

M. Schulz,[1] T. Ferger,[2] D. Fischer,[2,3] R. Moshammer,[2] and J. Ullrich[2]
[1]*University of Missouri-Rolla, Physics Department and LAMOR, Rolla, Missouri 65409, USA*
[2]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[3]*Stockholm University, Atomic Physics, Alba Nova, S-106 91 Stockholm, Sweden*
(Received 3 July 2006; published 5 October 2006)

We studied simultaneous electron ejection from both collision partners in 200-keV H^-+He collisions in a kinematically complete experiment by measuring the fully momentum-analyzed recoil ions and both active electrons in coincidence. The data were analyzed in terms of Dalitz spectra, in which the momentum exchange between three particles is plotted simultaneously in a single spectrum. We found that the energy transfer occurs predominantly between the active electrons, but most of the momentum is exchanged in elastic scattering between the cores of the collision partners.

DOI: 10.1103/PhysRevA.74.042705 PACS number(s): 34.50.Fa, 34.10.+x

I. INTRODUCTION

Ionization processes are particularly suitable to study the fundamentally important few-body problem [1,2]. The advantage over, e.g., excitation or capture reactions is that the final state involves at least three unbound particles (the scattered projectile, the ejected electron, and the residual target ion). Here, the kinematics and dynamics of the collision are more complex evolving over larger spatial extensions than in cases where the final state involves only two unbound particles, one of which often being neutral. As a result, higher-order effects tend to be more pronounced in ionization processes. To some extent, this larger complexity actually is a detriment as it introduces challenges to both theory and experiment. On the other hand, this complexity can lead to rich structures in the cross sections and often the qualitative dependencies readily provide valuable information about the collision dynamics.

In recent years, tremendous progress has been achieved in studies of single target ionization by ion impact. With the advent of cold target recoil-ion momentum spectroscopy [3], kinematically complete experiments have become feasible [4]. Since then, many measured data sets on fully differential cross sections (FDCS) for single ionization have been obtained [1,5–13]. In spite of significant theoretical efforts and progress [e.g., Refs. [12–20]], the comparison between experiment and theory revealed that our understanding of single ionization is not nearly as complete as assumed previously. From an experimental point of view it is important to now increase efforts, apart from further systematic studies of single ionization, on studies of more complex ionization processes, like double target ionization and simultaneous electron ejection from both collision partners in collisions with structured projectiles. Both reactions correspond to a transition from effective three-body to four-body processes.

In the case of simultaneous electron ejection from both collision partners, very few multiple differential data are currently available [21–23]. Only very recently, we reported multiple differential measurements for negative-ion impact, which was performed for 200-keV H^-+He collisions [24]. In that work we presented the longitudinal momentum spectra of both ejected electrons and double differential distributions of the mutual angles between two of the various collision fragments. The most important results of that work can be summarized as follows: simultaneous electron ejection through a direct interaction between the two active electrons is more important than ejecting both electrons independently by an interaction with the respective core of the other collision partner. Second, in the plane perpendicular to the initial beam direction (azimuthal plane) the momentum transfer to the electrons in the collision is small compared to their momentum distribution in the initial bound states of the He atom and H^- ion, respectively. Third, in the azimuthal plane the strongest angular correlation occurs between the two cores of the collision partners.

Although the data of Ref. [24] readily provided valuable information about the dynamics of simultaneous electron ejection from both collision partners, they are also subject to (among others) two limitations: first, the mutual angular distributions in the azimuthal plane relate the directions of the momenta of the corresponding particles to each other, but not their magnitudes. Second, these angular distributions show correlations between two particles rather effectively, but three- or four-particle correlations cannot easily be identified. In the case of pure target ionization we have recently demonstrated that Dalitz plots are a powerful tool to overcome both limitations [25]. There, the relative squared momenta of all three collision fragments are plotted simultaneously in a single spectrum. In this paper, we report measured Dalitz plots for simultaneous electron ejection from both collision partners in 200-keV H^-+He collisions. Since here, the final state involves four collision fragments we combine the momenta of the H^0 core and the ejected projectile electron for the Dalitz plot representing the target ionization and the momenta of the He^+ and the target electron for the plot representing electron ejection from the projectile.

II. EXPERIMENT

The experiment is described in detail in Ref. [24]. In short, a 200-keV H^- beam was crossed with a very cold (T

<1 K) neutral He beam from a supersonic gas jet with a density of about 10^{11} atoms/cm^2. The neutralized projectiles were selected by a switching magnet and detected by a channel plate detector. The recoil ions and the ionized electrons were extracted in the longitudinal direction (z direction, defined by the initial projectile direction) by a weak electric field of 2.3 V/cm. A uniform magnetic field of 20 G confined the transverse motion of the electrons so that all electrons with a transverse momentum of less than 3 a.u. hit the detector. The momentum vectors of the recoil ions and the ejected electrons were determined by using position sensitive detectors and time of flight techniques, where a fast signal from the projectile detector served as a timing reference. Both ejected electrons were detected simultaneously with a single detector employing a multihit technique (dead-time $\approx$10 nsec). In the longitudinal direction, the momentum resolution was approximately 0.2 a.u. and 0.1 a.u. for the recoil ion and for the electrons, respectively. In the direction of the jet expansion (y direction), the corresponding numbers are 0.3 a.u. and 0.1 a.u. and for the x direction 0.2 a.u. and 0.1 a.u., respectively (in all cases the full width at half maximum is provided). The momentum of the neutralized projectiles was determined from momentum conservation.

III. RESULTS AND DISCUSSION

Originally, Dalitz plots were applied to three particles of equal or similar mass in particle physics [27] and later used to analyze triple ionization in atomic collisions [28]. There, the relative energy ε_i of each particle normalized to the sum energy of all three particles is plotted in a coordinate system consisting of an equilateral triangle, where each triangle side represents one particle. For a given data point ε_i for each particle is given by the perpendicular distance of that data point to the corresponding triangle side. For the case of three particles with very different mass, like in, e.g., single target ionization, we have recently developed a refinement of this approach [25]. Instead of the ε_i, the relative squared momenta $\pi_i = p_i^2/\Sigma p_j^2$ of the three collision fragments were plotted. In the case of the projectile, the difference between the initial and final momenta was used.

In simultaneous electron ejection from both collision partners an additional complication is presented by the fact that the final state involves four unbound particles. We therefore present separate Dalitz plots to analyze He-electron and H^--electron ejection. In the case of He-electron ejection, the subsystem consisting of the H^0 core and the ejected H^- electron (assumed to be the faster of the two ejected electrons) are treated as a single composite H^- particle with a momentum equal to the sum of the momenta of the H^0 core and of the projectile electron. This sum momentum $\mathbf{p}_{H^-}$ in the initial projectile rest frame is equal to the momentum transfer $\mathbf{q}_{H^-}$ to the target atom. Likewise, in the plot for H^- electron ejection we treat the He^+ ion and the ejected He electron (i.e., the slower of the two ejected electrons) as a single composite He^0 particle. In the initial target atom rest frame the sum momentum $\mathbf{p}_{He^0}$ is equal to the momentum transfer $\mathbf{q}_{He^0}$ to the projectile and $\mathbf{q}_{He^0} = -\mathbf{q}_{H^-}$.

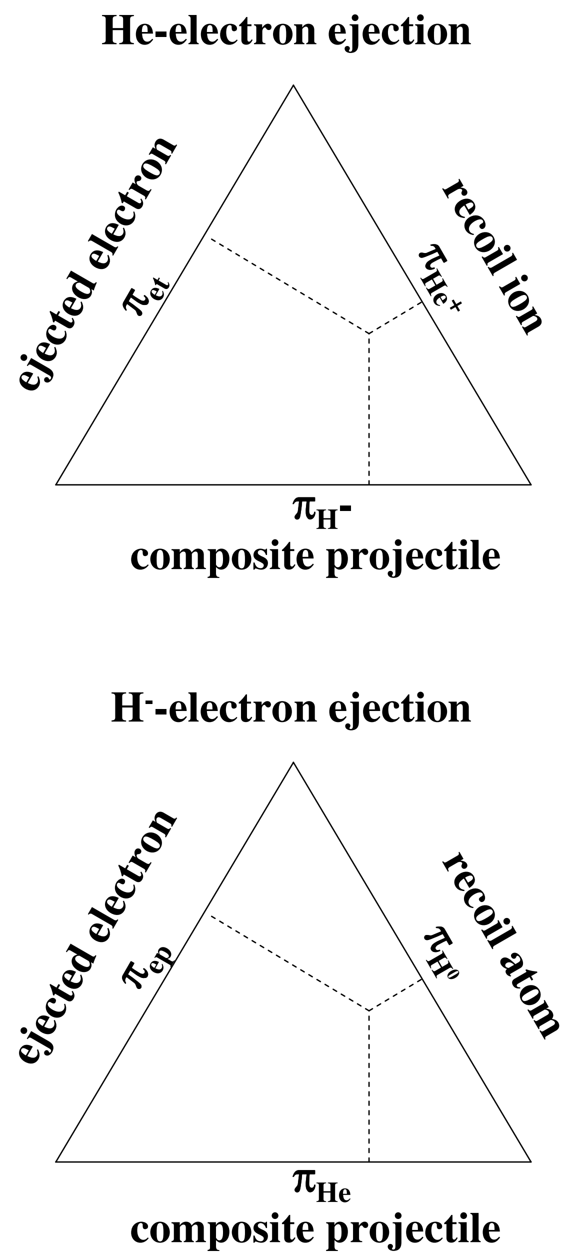

FIG. 1. Illustrative schematic Dalitz plot for He- (top) and H^--electron ejection (bottom). For He-electron ejection the H^- ion is denoted as the composite projectile and the He^+ as the recoil ion. Likewise, for H^--electron ejection the He atom is denoted as the composite projectile and the H^0 as the recoil atom. With this notation, the ejected electron, the composite projectile, and the recoil ion (atom) correspond to the same triangle side in both plots. The values of the relative squared momenta π_i for a given data point are given by the perpendicular distance to the respective triangle side (dashed lines).

In Fig. 1 we show a schematic Dalitz plot in order to show how to read the experimental spectra. First we note that the role of projectile and recoil ion (or atom) is reversed for H^--electron ejection relative to He-electron ejection. In the following, we refer to the projectile as the composite heavy particle causing the ejection of the respective electron. Likewise, the recoil ion (atom) is the core of the collision partner

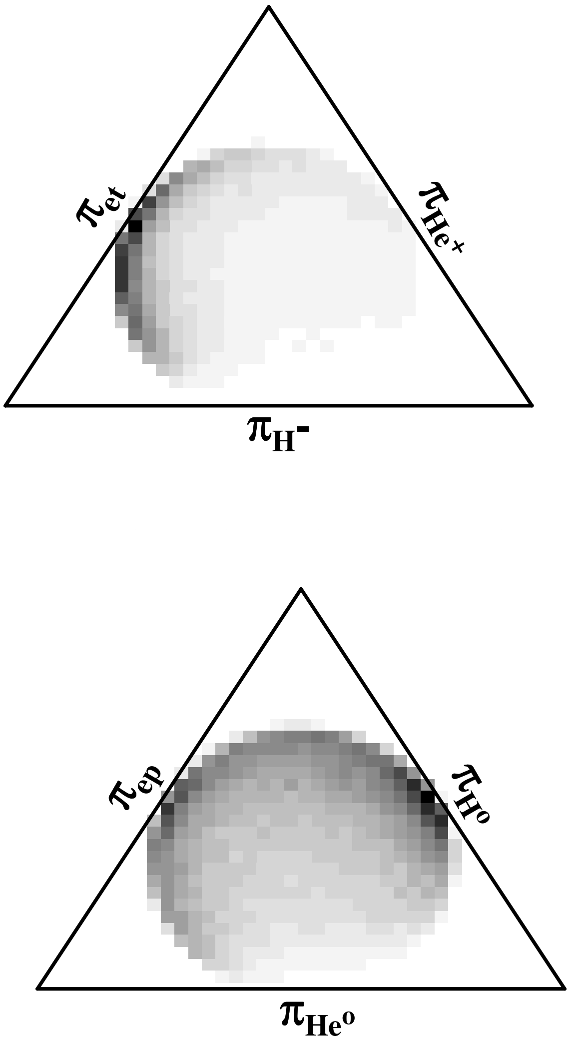

FIG. 2. Dalitz plots for He-electron ejection (top) and H^--electron ejection (bottom) occurring simultaneously in 200-keV H^-+He collisions. For Dalitz coordinates see text.

which the considered ejected electron was initially bound to. More specifically, in the case of H^--electron ejection He^0 is the composite projectile and H^0 is the recoil atom, while for He-electron ejection H^- is the projectile and He^+ the recoil ion. With this notation, in our Dalitz plots the ejected electron is always represented by the left triangle side, the composite projectile by the lower triangle side, and the recoil ion (atom) by the right triangle side.

In Fig. 2 we show the Dalitz plots for He-electron (top) and H^- electron ejection (bottom). For both plots, the momenta of the ejected H^- electron and the H^0 core are given in the rest frame of the initial H^- particle. It should be noted that only the region inside the inner circle (i.e., the circle which touches all triangle sides) is kinematically allowed. For the regions outside that circle momentum is not conserved.

The Dalitz plots for both He- and H^--electron ejection are qualitatively different from those reported earlier for pure target ionization by fast positive ion impact [25]. In the latter, the dominant structure is a strong peak at the triangle side representing the projectile, i.e., the momentum transfer by the projectile is typically small compared to the momenta of the target fragments. This peak is indicative of a strong internal momentum correlation between the electron and the target core originating in the initial bound state and surviving the collision. This feature is very similar to photoionization, since the incoming photon carries essentially no momentum so that the momenta of the target fragments results from their momentum distributions in the initial bound state. In the present data for simultaneous electron ejection from both collision partners, in contrast, essentially no flux at all is seen near the lower triangle side illustrating that the momentum transfer by the respective composite projectile (H^- or He^0) is relatively large. As a result, for both collision partners the internal correlation is not as clearly seen as in pure target ionization by fast ion impact. Both spectra, especially the one for He-electron ejection, show a peak at the left triangle side, i.e., for very small π_{et} or π_{ep} which is equivalent to $\pi_{H^-}=\pi_{He^+}$ and $\pi_{H^0}=\pi_{He^0}$, respectively. This corresponds to a situation where a large momentum exchange in the collision occurs between the composite projectile and the recoil ion or atom (i.e., between H^- and He^+ and between He^0 and H^0, respectively). In the case of H^--electron ejection a second, even larger peak is seen near $\pi_{H^0}=0$, illustrating important contributions from binary interactions between the He^0 atom and the H^- electron.

In order to explore whether for H^--electron ejection momentum is predominantly transferred by the electron or the core of the composite He^0 projectile to the H^0 core, we show in Fig. 3(a) a Dalitz plot generated with the additional condition that $p_{He^+}>3p_{et}$. In this spectrum the relative intensity between the peaks near $\pi_{ep}=0$ and $\pi_{H^0}=0$ is shifted in favor of the $\pi_{ep}=0$ peak. It is thus clear that a significant momentum exchange occurs between the two cores of the collision partners.

The data of Fig. 3(a) do not exclude the possibility that there is a significant momentum exchange between the electron of the He^0 projectile and the H^0 core as well. In Fig. 3(b) we therefore present Dalitz plots with the condition $p_{et}>3p_{He^+}$. This plot is qualitatively different from those in Figs. 2 and 3(a). The data are much more spread out over the kinematically allowed circle than for the condition $p_{He^+}>3p_{et}$ demonstrating an increased importance of simultaneous momentum exchange between three or even all four collision fragments. Furthermore, the peak near the left triangle side no longer occurs at $\pi_{ep}=0$, but rather it is shifted towards the lower triangle side corresponding to a slightly increased π_{ep} and slightly decreased π_{He^0}. Most importantly, the peak at the right triangle side in Fig. 2 is completely removed.

To understand the shift of the peak at the left and the elimination of the peak at the right triangle side by the condition $p_{et}>3p_{He^+}$ it is helpful to analyze the region of the Dalitz plot enclosed by the dashed lines indicated in Fig. 3(b), the left half of the lower triangle side, and the lower half of the left triangle side. We label this region I and the remaining part of the Dalitz plot region II. For all events falling in region I the momentum of the H^0 recoil atom is larger than both the ejected H^- electron and the composite He^0 projectile. Since momentum conservation yields $\mathbf{p}_{ep}+\mathbf{p}_{H^0}=-\mathbf{p}_{He^0}=\mathbf{q}_{He^0}$ for the rim of the circle (i.e., where the

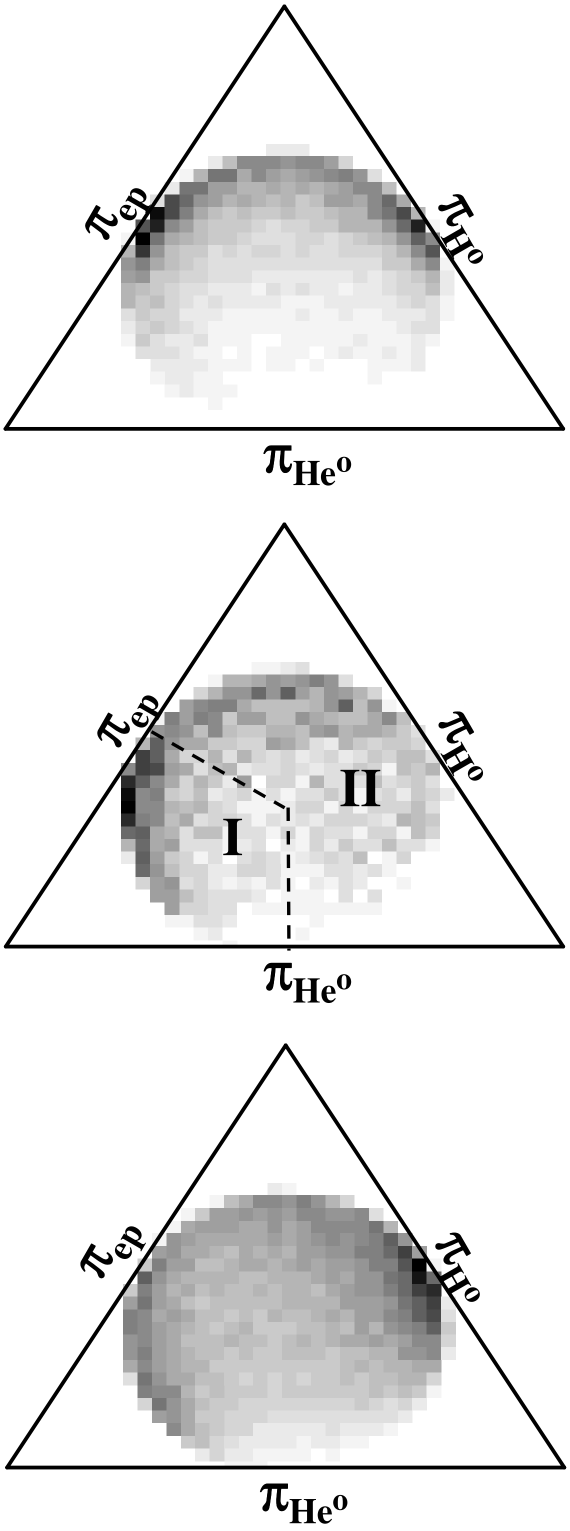

FIG. 3. Dalitz plots for H^--electron ejection for the conditions (a) $p_{He^+} > 3p_{et}$, (b) $p_{et} > 3p_{He^+}$, and (c) $0.5 < p_{He^+}/p_{et} < 2$.

peak occurs) this is only possible if the ejected electron momentum is pointing opposite to $\mathbf{q}_{He^0}$. For pure target ionization, such events are seen in the fully differential angular ejected electron distributions as the so-called recoil peak [1,5–13]. Likewise, for events falling on the rim in region II the electron momentum must be pointing in the same direction as $\mathbf{q}_{He^0}$. In the fully differential angular ejected electron distributions such events lead to the binary peak. Therefore, the shift of the peak near $\pi_{ep}=0$ and the elimination of the peak near $\pi_{H^0}=0$ clearly show that if momentum is mainly transferred from the electron (rather than the core) of the He^0 projectile to the H^- ion the recoil peak is significantly enhanced relative to the binary peak. This is consistent with a theoretical higher-order analysis of FDCS for single ionization. There it is found that for electron impact the intensity in the recoil peak relative to the binary peak is enhanced by higher-order effects while for ion impact it is suppressed [26].

It should be noted that the peak at $\pi_{H^0}=0$ for H^--electron ejection represents binary interactions in a stricter sense than the binary peak in the FDCS. The latter merely implies that the direction of the electron momentum is close to the direction of the momentum transfer, but the magnitudes can generally be quite different. Therefore, the term binary peak is somewhat misleading as at least a third particle may carry significant momentum. In contrast, the peak at $\pi_{H^0}=0$ implies that both direction and magnitude are approximately the same and the term binary peak appears to be more justified for this maximum. Usually the binary peak in this stricter sense is very difficult to observe. Here, it is very pronounced for H^--electron ejection because of the very small binding energy, i.e., the H^- electron behaves almost like a free electron. It is, however, interesting to note that the binary peak is strongly suppressed for both conditions $p_{He^+} > 3p_{et}$ and $p_{et} > 3p_{He^+}$, i.e., the binary peak is neither due to a binary interaction with the electron nor with the core of the He^0 projectile. It therefore must be due to a binary interaction with the entire He atom. Indeed, the Dalitz plot for H^--electron ejection generated with the condition $0.5 < p_{He^+}/p_{et} < 2$, which is shown in Fig. 3(c), is dominated by the binary peak and the maximum at $\pi_{ep}=0$ is eliminated. Furthermore, the integrated intensity of Fig. 3(c) is much larger than the integrated intensities in Figs. 3(a) and 3(b) (i.e., for the conditions $p_{et} > 3p_{He^+}$ and $p_{He^+} > 3p_{et}$). Therefore, H^--electron ejection is predominantly caused by an impact with the entire He^0 atom.

For He-electron ejection we did not find significant qualitative changes of the Dalitz plots for the equivalent conditions $p_{ep} > 3p_{H^0}$, $p_{H^0} > 3p_{ep}$, and $0.5 < p_{H^0}/p_{ep} < 2$. Therefore, in He-electron ejection momentum is always predominantly transferred to the He^+-recoil ion, either by the H^0 core, by the projectile electron, or by the composite H^- projectile.

At first glance, the discussion of Fig. 3(c) appears to be in conflict with the longitudinal electron momentum spectrum which we presented earlier [24]. There, clear signatures of a binary electron-electron interaction were found for the ejected H^--electron spectrum, which was also consistent with a first-order calculation only accounting for that interaction. In an attempt to resolve this apparent conflict we analyzed the Dalitz plots for the longitudinal and transverse components of the involved momenta separately, which are shown in Fig. 4. In the Dalitz coordinates $\pi_i = p_i^2/\Sigma p_j^2$ the p_i and p_j are now the longitudinal (top) and transverse (bottom) com-

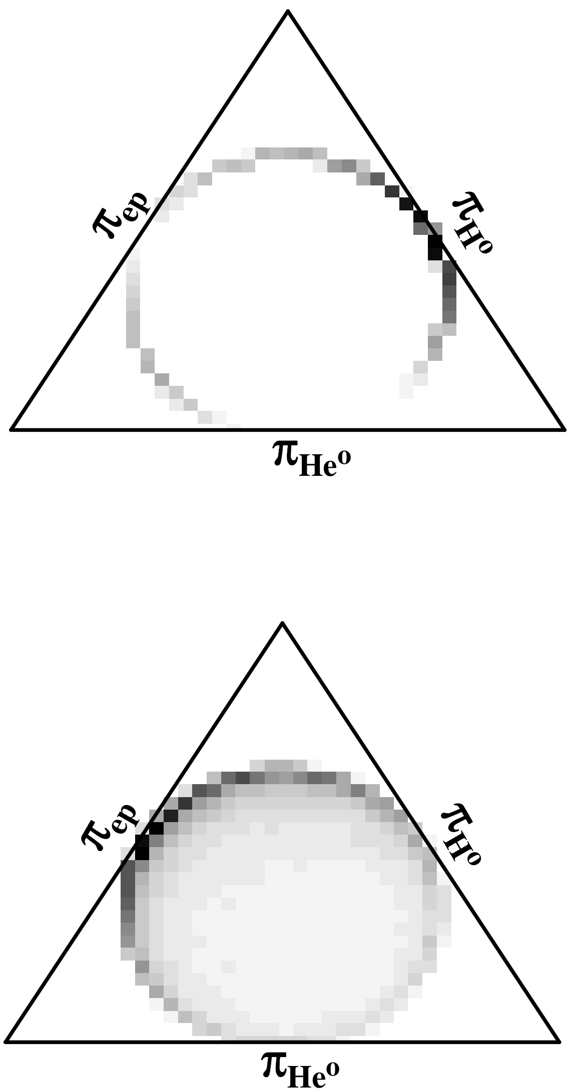

FIG. 4. Dalitz plots for the longitudinal (top) and transverse (bottom) components of the momenta of the collision fragments for H^--electron ejection.

ponents of the corresponding momenta (it should be noted that in the longitudinal direction only the rim of the inner circle is kinematically allowed because the motion is restricted to one dimension, while in the transverse direction it is only restricted to two dimensions). The difference between these two components is quite obvious: in the longitudinal direction the spectrum is clearly dominated by a peak at $\pi_{H^0}=0$ and the peak at $\pi_{ep}=0$ is completely absent (in fact, there is a minimum at $\pi_{ep}=0$). Likewise, in the transverse direction the spectrum is clearly dominated by a peak at $\pi_{ep}=0$ and the peak at $\pi_{H^0}=0$ is completely absent. For the longitudinal component the dominance of the peak at $\pi_{H^0}=0$ remains even for the condition $p_{et}>3p_{He^+}$. Therefore, the importance of binary electron-electron collisions in the longitudinal direction is confirmed by our Dalitz plots. In contrast, in the transverse direction momentum exchange occurs predominantly between the cores of the collision partners. Since the longitudinal momentum transfer is essentially determined by the energy loss, this observation shows that the energy exchange in simultaneous electron ejection from both collision partners occurs almost exclusively between the electrons. The cores only scatter elastically off each other without transferring a significant amount of energy.

IV. CONCLUSIONS

We have presented Dalitz plots for He- and H^--electron ejection occurring simultaneously in 200-keV H^-+He collisions. These plots are very effective in analyzing the momentum exchange between three particles simultaneously in a single spectrum. Our results confirm a strong correlation between the two cores of the collision partners which we had identified earlier in double differential angular distributions [24]. In addition, with the Dalitz plots we were able to also identify a strong binary interaction between the H^- electron and the composite He^0 projectile, while we found no indication for a significant momentum exchange between the He electron and the composite H^- projectile. Finally, the Dalitz plots for the longitudinal and transverse momentum components revealed that the energy exchange occurs predominantly between the two active electrons and it is accompanied by strong elastic scattering between the cores of the collision partners.

ACKNOWLEDGMENTS

This work was supported by the Mercator Program of the Deutsche Forschungsgemeinschaft, the Gesellschaft für Schwerionenforschung, and the National Science Foundation under Grants Nos. PHY-0353532 and INT-0224943.

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