Simultaneous Projectile-Target Ionization: A Novel Approach to (e, 2e) Experiments on Ions

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A kinematically complete experiment for simultaneous ionization of a projectile and target has been performed for 3.6 MeV/u C^{2+} on He collisions measuring the final vector momenta of the He^{1+} recoil ion and of two electrons (projectile, target) in coincidence with the emerging C^{3+} projectile. The feasibility of an event-by-event separation of the various reaction channels, among them the ionization of C^{2+} by the interaction with a quasifree target electron, is demonstrated in agreement with six-body classical trajectory Monte Carlo calculations, paving the way to kinematically complete electron-ion scattering experiments.

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The ionization of ions by electron impact is one of the most fundamental processes in atomic collision physics. This reaction has enormous practical importance and far-reaching technical consequences for the understanding and modeling of all astrophysical as well as terrestrial plasmas including those in fusion reactors. Whereas total cross-section measurements for ionization as well as recombination in ion-electron collisions have become routinely feasible in the electron-cooler sections of storage rings [1], differential cross sections were restricted to angular distributions of scattered electrons in slow collisions with lowly charged ions [2]. Investigations differential in the momenta of more than one of the outgoing particles are not at hand. Kinematically complete measurements, that illuminate the target structure and the collision dynamics in ultimate detail in so-called $(e, 2e)$ experiments [3], have been beyond any imagination for electron-ion collisions: Even in storage rings, the reachable luminosity is too low by orders of magnitude using crossed ion-electron beams arrangements along with conventional detection techniques for the emerging particles.

On the other hand, in energetic ion-atom and molecule-atom collisions the importance of effective electron collisions, i.e., the interaction between a target-electron and a projectile, has been pointed out very early by Bates and Griffing [4] and Gallagher [5]. Since then it has been explored theoretically (see, e.g., [6–9]) as well as experimentally in numerous publications. After a first experimental identification of the process in ion-atom collisions by means of the velocity (v_p) dependence of total projectile ionization cross sections due to its threshold behavior [10]—the energy of the active target electron relative to the projectile ion ($E_e = \frac{1}{2}v_p^2$; in atomic units: a.u.) has to be larger than the lowest ionization potential of the ion—many investigations concentrated on the identification of this contribution by the appearance of characteristic transition lines in high-resolution zero-degree electron spectra [11] or by its specific kinematic signatures [12]. Thus, calculations indicate [13] that the (e, e) interaction dominates the cross section for projectile ionization at large internuclear distances b since the nuclear potential of the target, that might cause ionization of the projectile in an (n, e) interaction as well, is effectively screened by the target electrons as illustrated in the upper part of Fig. 1. In addition, the (e, e) contribution (also termed "antiscreening" in literature due to the above effect) leaves the target nucleus as a spectator without any significant final momentum, whereas it noticeably "recoils" if the screened target nuclear potential takes over the active part in the (n, e) reaction at smaller b ("screening").

Two recent experiments, measuring the target (recoil-) ion momentum $(\mathbf{P}_T)$ distribution after simultaneous projectile-target ionization [14] were able to identify two maxima in the doubly differential recoil-ion momentum cross section [15,16]. Their location was closely related

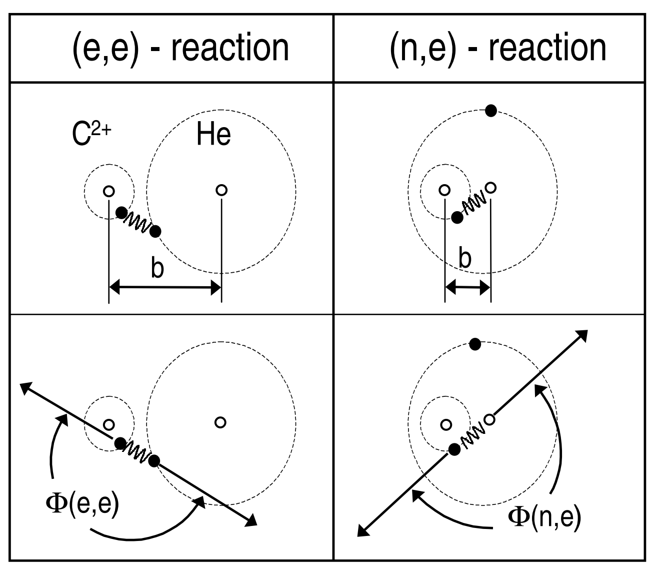

FIG. 1. Schematic illustration of the kinematics for (e, e) and (n, e) contributions to projectile ionization (see text).

to those expected from target-ion kinematics for each of the processes and essentially reproduced by n-electron classical trajectory Monte Carlo calculations (nCTMC) with two active electrons on the He target and one on the projectile. Surprisingly, close to threshold, where the two maxima are observed, the calculations were found to be in quantitative agreement with the experiments only if an additional reaction channel, double target ionization plus electron exchange, was taken into account. In the calculations, this channel displayed similar recoil-ion kinematics as the (e, e) contribution. Thus, while proving that (n, e) and (e, e) mechanisms at least in principle do have different kinematic signatures, it was impossible to isolate one of them in a certain collision on the basis of a $\mathbf{P}_T$ measurement alone.

In this Letter, we report on a kinematically complete measurement for simultaneous single ionization of the projectile and of the target in C^{2+} on He collisions at 3.6 MeV/u ($v_p = 12$ a.u.), well above the (e, e) threshold ($v_p^{\rm thres} = 3$ a.u.). Nearly 50 years after its first prediction, it is now demonstrated in close accordance with nCTMC results that we are able to clearly isolate all collision events where the (e, e) reaction dominantly contributes by comparing event-by-event the momentum transfer to the target nucleus $\mathbf{P}_T$ relative to the ionized target electron $\mathbf{P}_{\rm Te}$. It is further shown that these events essentially display all features usually observed in $(e, 2e)$ experiments in electron-atom collisions paving the way to future $(e, 2e)$ investigations for all ions over a large velocity regime in heavy-ion storage rings.

The experiment was performed at the UNILAC (universal accelerator) of GSI (Gesellschaft für Schwerionenforschung, Darmstadt) guiding a 3.6 MeV/u C^{2+} beam onto a supersonic He gas-jet target ($\sim 10^{11}$ atoms/cm^2) in the Reaction-Microscope. Projectile ionization was identified by separating the emerging C^{3+} ions in a magnet and detecting them with a fast scintillation counter. In the GSI-Reaction-Microscope [17] the vector momenta of all other collision fragments, of the fast projectile electron $\mathbf{P}_{\rm Pe}$, of the low-energy target electron $\mathbf{P}_{\rm Te}$, and of the target nucleus $\mathbf{P}_T$ have been detected in coincidence with the emerging C^{3+} ions over the major part of the twelve-dimensional four-particle final-state momentum space. Both electrons and the target ion are guided by parallel electric (2 V/cm) and magnetic fields (33 G) onto microchannel plate detectors (ions: diameter = 40 mm; electrons: diameter = 80 mm) placed in opposite directions along the projectile beam propagation. Longitudinal (parallel to the beam propagation, $P_\parallel = P_z$) and transverse (P_x, P_y) momentum components for all three fragments are obtained from their absolute times-of-flight and detection positions, respectively. Both emitted electrons, the fast one moving with about projectile velocity into the forward direction at an approximate energy of 2 keV ("cusp-electron" in the literature), as well as the slow target electron with typical energies of less than 100 eV being emitted in all directions, are efficiently detected by one of the multihit capable microchannel plates in the forward direction. The solid angle is 4π for all projectile electrons with $E'_{\rm Pe} < 200$ eV measured in the projectile frame (Σ') that moves with 12 a.u. in the longitudinal direction relative to the laboratory frame (Σ). All target electrons are recorded for longitudinal momenta $\mathbf{P}_{\parallel \rm Te} > -1.5$ a.u. and transverse momenta of $P_{\perp \rm Te} = (P_{x\rm Te}^2 + P_{y\rm Te}^2)^{1/2} < 4$ a.u. (Σ) contributing to more than 90% to the total target-ionization cross section. For the recoiling He^{1+} ions $\Delta\Omega_T = 4\pi$ for $|\vec{P}_T| \leq 8$ a.u. (Σ). Momentum resolutions are better than $|\vec{P}'_{\rm Pe}| \leq \pm 0.5$ a.u., $|\vec{P}_{\rm Te}| \leq \pm 0.2$ a.u., and $|\vec{P}_T| \leq \pm 0.2$ a.u. for the projectile electron (Σ'), the target electron (Σ), and recoil ion (Σ), respectively.

As schematically illustrated in the lower part of Fig. 1, (e, e) and (n, e) contributions to projectile ionization are expected to differ in the correlated dynamics of the active particles: Whereas the active target electron should dominantly compensate the major part of the momentum transfer $\vec{q}$ to the C^{2+} projectile in an (e, e) ionization event, this role will be taken by the target nucleus if the (n, e) interaction dominates. Hence, since $\vec{q} = -(\vec{P}_T + \vec{P}_{\rm Te})$, the criterion that $|\vec{P}_T| \geq |\vec{P}_{\rm Te}|$ or vice versa might indicate the active role of one or the other emerging target fragment. In order to substantiate this supposition, we have inspected the azimuthal angles which the projectile electron includes with the target electron $\Phi(e, e)$ or the target-ion $\Phi(n, e)$, respectively. As illustrated in the lower part of Fig. 1 the particular fragment taking over the active role in a certain collision is expected to be scattered predominantly opposite to the ionized projectile electron in the azimuthal plane.

In Fig. 2 measured as well as calculated angles $\Phi(e, e)$ are plotted versus $\Phi(n, e)$ in two-dimensional representations for all events (upper row), for events with $|\vec{P}_{\rm Te}| \geq |\vec{P}_T|$ where the (e, e) process is expected to dominate (middle row), and for $|\vec{P}_{\rm Te}| \leq |\vec{P}_T|$ (lower row), where the target nucleus might take over the active part. Surprisingly, even without any condition (left upper frame), a significant pattern is observed indicating that two-particle interactions during the collision dominate the complicated four-particle dynamics. Applying only one additional requirement, namely that $|\vec{P}_{\rm Te}|$ is larger or smaller than $|\vec{P}_T|$, divides a major part of all events into two clearly separated regimes where *either* $\Phi(e, e)$ *or* $\Phi(n, e)$ is close to 180° for $|\vec{P}_{\rm Te}| \geq |\vec{P}_T|$ (middle) or $|\vec{P}_{\rm Te}| \leq |\vec{P}_T|$ (bottom), respectively. These two regimes can be uniquely related to collisions where either the (e, e) or the (n, e) process dominates projectile ionization.

The experimental results (left column) are in excellent agreement with theoretical predictions of six-body CTMC calculations that include the two nuclei, the He electrons, and the L-shell electrons on C^{2+} (middle column). Here, the target as well as the projectile electrons are bound by their respective ionization potentials and move on classical

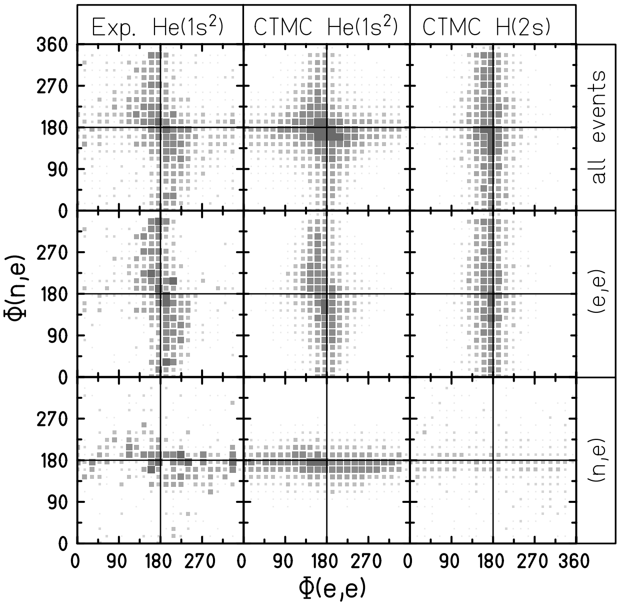

FIG. 2. Azimuthal angle between projectile electron and target He^{1+} recoil-ion $\Phi(n,e)$ versus azimuthal angle between emitted target and projectile electrons $\Phi(e,e)$ for 3.6 MeV/u C^{2+} on He (1 s^2) collisions (left column: experiment; middle column: CTMC) and for 3.6 MeV/u C^{2+} on H (2 s) collisions (right column: CTMC). The Z scale is logarithmic with ten steps from the minimum to the maximum cross section in each column represented by different sizes of the symbols. Upper row: All events. Middle row: $|\vec{P}_{\mathrm{Te}}| \geq |\vec{P}_T|$. Lower row: $|\vec{P}_{\mathrm{Te}}| \leq |\vec{P}_T|$.

Kepler orbits around their nuclei in microanonical distributions. During the collision all interactions between centers for the six active particles are explicitly taken into account. Only the electron-electron interactions on individual centers were approximated by using a simple screened Coulomb potential between the electron and its parent nucleus [9]. Even details in the data, such as systematic variations of the mean value for $\Phi(n,e)$ and $\Phi(e,e)$ around 180° or the $\Phi(n,e)$ dependent variation in intensity for the (e,e)-events are reproduced by theory.

While the dominating two-body interactions (e,e) or (n,e) can indeed be identified in each single collision for a major part of the events, the latter features clearly demonstrate, however, that three- or four-body interactions are still important in the present, quite symmetric collision system with comparable binding energies of both electrons. They noticeably modify the dynamics in the final state, are interesting by themselves, but are "disturbing" in the present context, where the main purpose is to isolate the (e,e) process and demonstrate the feasibility of clean differential electron-ion scattering experiments. Therefore, we have performed a Monte Carlo calculation for a cleaner system with much more asymmetric binding energies, namely for 3.6 MeV/u C^{2+} on H collisions with the active hydrogen electron in an excited $n = 2$ state. Significant changes are observed: First, the importance of the (n,e) reaction is drastically reduced; second, the $\Phi(e,e)$ angular distribution is always found to be exactly peaked at 180° independent of $\Phi(n,e)$; and third, the recoiling-target ion is isotropically scattered with respect to the projectile electron. The latter two indicate that the recoil ion now has perfectly taken over the role of a spectator, not being noticeably involved.

Having demonstrated that a separation of (e,e)-dominated events is feasible, we can select this channel using the condition $|\vec{P}_{\mathrm{Te}}| \geq |\vec{P}_T|$ and investigate to what extent this specific subset of events does resemble characteristic features typically observed in electron-impact ionization. Modifications due to three- or four-body interactions are neglected for the moment. Thus, in the following we consider electron-impact ionization of the projectile ion in inverse kinematics, i.e., the target electron is interpreted as a quasifree electron hitting the ionic projectile with an energy of about 2 keV in the projectile frame Σ'. In the $(e,2e)$ literature, investigations of the collision dynamics have mainly been performed in so-called coplanar geometry, where the ionized target electron is emitted into a plane defined by the momentum transfer $\vec{q}$ and the incoming electron momentum vector $\vec{P}_{ei}$. Accordingly, a second condition was set for coplanar geometry with an azimuthal acceptance of $\pm 20^{\circ}$. The crucial quantity characterizing an electron collision is $\vec{q} = \vec{P}_{ei} - \vec{P}_{ef}$, the difference between the incoming and scattered electron momentum vectors, and can be uniquely determined as $\vec{q} = -(\vec{P}_T + \vec{P}_{\mathrm{Te}})$.

In Fig. 3 results are shown for coplanar geometry in a two-dimensional representation plotting the scaled momentum transfer $|\vec{q}^{\,*}| = q(2U_b)^{-1/2}$ versus the polar emission angle ϑ_e of the target electron with respect to the momentum-transfer direction for electron-impact ionization of C^{2+} (Fig. 3a) and for 2 keV electron on He collisions (Fig. 3b). The momentum transfer has been scaled to take into account the different ionization potentials U_b in both systems. Striking similarities are observed: First, the major part of the electrons is emitted with a polar emission angle close to 0° with respect to $\vec{q}$. This is the so-called "binary peak," where the target electron can be considered to be ejected as a result of a binary collision with the projectile electron. It appears as a characteristic feature for ionization of electrons with zero orbital angular momentum in all $(e,2e)$ investigations and is centered along the momentum transfer direction at collision energies well above the threshold. At a scaled momentum transfer of $\vec{q}^{\,*} \leq \approx 1$ another structure becomes visible, with a maximum intensity at an emission angle about opposite to the binary peak. Again this is a characteristic feature, the so-called "recoil peak," which is found only for small momentum transfers. Here, the electron is found to be emitted into the $-\vec{q}$ direction due to its interaction with the recoiling target nucleus balancing both the momentum transfer and the ejected electron momentum. For a detailed analysis and comparison to theory the outgoing electron

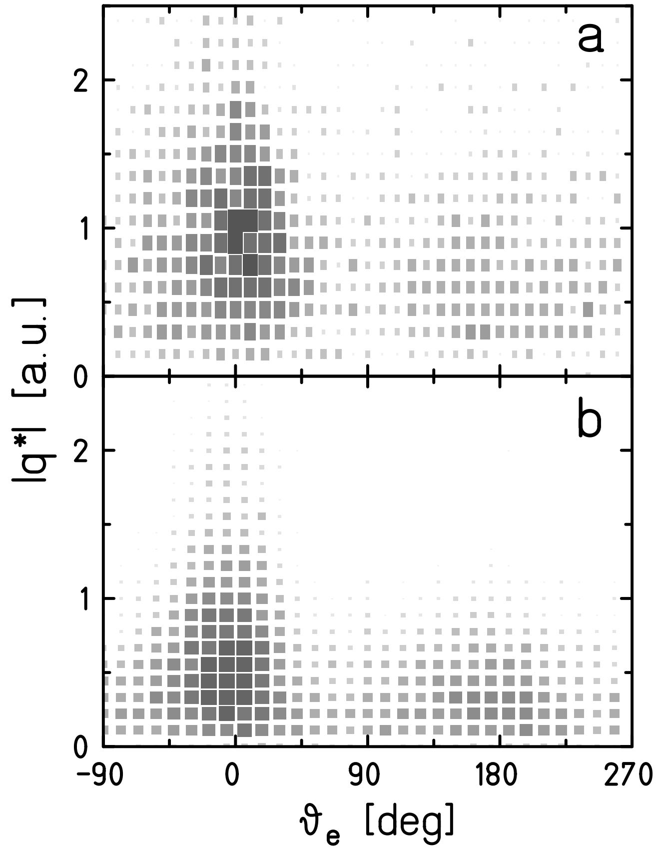

FIG. 3. Amount of the scaled momentum transfer q^* (see text) versus angle ϑ_e between $\vec{q}$ and the emitted electron in coplanar geometry for C^{2+} ionization (a) in inverse kinematics for simultaneous projectile and target ionization with $|\vec{P}_{\mathrm{Te}}| \geq |\vec{P}_T|$ and He ionization (b) by 2 keV electron impact (see text). The Z scale is logarithmic with ten steps from the minimum to the maximum cross section in each column represented by different sizes of the symbols.

energy is usually fixed in addition. Cuts for well-defined momentum transfers then provide fully differential cross sections where the kinematics of the collision is completely determined. This ultimate information can in principle be extracted from the present data set but the statistical significance is too low in this pilot experiment.

In conclusion, we have presented results of a kinematically complete experiment on simultaneous projectile-target ionization in fast ion-atom collisions. It is demonstrated that the contribution of the (e, e) interaction can be separated event-by-event by kinematically selecting collisions, where the target nucleus essentially remains passive. The subset of these events shows all characteristic features usually observed in electron-atom (molecule, solid) collisions indicating that this technique may provide the key to systematic $(e, 2e)$ investigations on ions. Presently, work is in progress to implement a Reaction-Microscope into the experimental storage ring (ESR) at GSI with an excited supersonic He jet target.

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