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Three-body momentum exchange in singly ionizing 2-MeV/u C^{6+}-helium collisions

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We study helium single ionization with emission of low-energy ($\varepsilon_k < 10$ eV) electrons in collisions with 2-MeV/u C^{6+} ions. We explore, both experimentally and theoretically, longitudinal and transverse momentum distributions of the final reaction products. We present in-depth discussion of mechanisms resulting in the forward-backward asymmetry in the longitudinal spectra of emitted electrons and recoil ions. By comparing our experimental data and calculations we display clear signatures of the interaction between the projectile and the target core (the *n*-*n* interaction) for the transverse distributions of the recoil ion and projectile. For the collision system in question the *n*-*n* interaction is shown to represent an important mechanism of the momentum exchange.

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I. INTRODUCTION

Collisions of ions (projectiles) with atoms (targets) represent one of the fundamental problems studied in atomic physics research. Among the interesting phenomena which can occur in such collisions is ionization where one or more target electrons are finally unbound.

In fast projectile-target collisions where the collision velocity v_p is much larger than the projectile charge Z_p, $\eta = Z_p/v_p \ll 1$, the standard first Born approximation (see, e.g., Refs. [1,2]) often represents an appropriate tool to analyze the different aspects of target ionization. Within this approximation the initial and final states of the colliding system are approximated by unperturbed projectile and target wave functions and the collision occurs via just a ''single interaction'' (or single-virtual-photon exchange) between the projectile and the target. Moreover, because of the orthogonality of the initial and final target states, the projectile interaction with the target nucleus does not contribute to target transitions [3] and, therefore, the single virtual photon has to be exchanged between the projectile and the target electrons (see, e.g., Ref. [1]).

When the effective perturbation strength η increases the application of the first Born approximation becomes questionable even for evaluations of total ionization cross sections. Using the language of perturbation expansion of the transition amplitude in powers of the projectile-target interaction, one can say that in such a case ''multiple'' interactions (or multiple-virtual-photon exchanges) between the projectile and the target electrons start to contribute substantially to the ionization process. Also the interaction between the projectile and the target nucleus (more precisely, the interaction between the projectile and the target core which consists of the target nucleus and ''passive'' target electrons) begins to influence the process.

The latter interaction (denoted below as the *n*-*n* interaction) is known to have a negligible influence on electron emission spectra (integrated over the projectile deflection angle) in high-velocity collisions. Despite this, the *n*-*n* interaction remains to be of great importance because of two main reasons. The first and fundamental reason is that it has to be included in order to give a proper treatment of the full collision dynamics. The second one is that this interaction is certainly necessary in order to give a correct description of the projectile scattering in solids (angular straggling, range distribution) which is of importance in various applications.

In this paper we present results of our experimental and theoretical study of helium single ionization by 2-MeV/u C^{6+} ions. We shall restrict our attention to exploring collisions accompanied by emission of low-energy ($\varepsilon_k < 10$ eV) electrons. For the collision system in question the effective perturbation strength $\eta = Z_p/v_p = 0.67$ is rather large. Therefore, very substantial deviations from results of first-order considerations, connected with multiple photon exchanges between the projectile and the target electrons as well as with the *n*-*n* interaction, are expected to take place. The main emphasis of the present study will be to elucidate the role of the *n*-*n* interaction in the formation of momentum spectra of scattered projectiles and recoil ions [4]. Atomic units are used throughout except where otherwise stated.

II. EXPERIMENTAL AND THEORETICAL BACKGROUNDS

A. Experiment

The experiment has been performed at the Tandem accelerator of the Max-Planck-Institute in Heidelberg using a multielectron recoil-ion momentum spectrometer (''reaction microscope'') which has been described in detail elsewhere [6]. The accelerator provided a well-collimated (1×1 mm^2), pulsed (pulse length ≈ 1 ns, repetition rate $= 180$ kHz) C^{6+} beam with an energy of 2 MeV/amu ($v_p \approx 9$ a.u.), which is crossed with a supersonic helium gasjet target in the reaction microscope. Electrons and target ions produced in the collision were extracted in opposite directions along the beam axis by a weak electric field (2.7 V/cm) and were detected by two-dimensional position sensitive multichannel plates. In addition, a solenoidal magnetic field of 6 G was applied oriented along the projectile beam direction to confine the electron transverse motion. In this way, all electrons with energies below 9 eV were forced onto the detector in a cyclotron motion and were detected with the full solid angle of 4π. From the measured position on the detector and the time of flight, the initial momenta of the extracted particles can be reconstructed. The achieved momentum resolution for the He^+ ions was $\Delta p_{R,\parallel}=0.1$ a.u. in the longitudinal and $\Delta p_{R,\perp}=0.3$ a.u. in the transverse direction, respectively. The electron longitudinal momentum resolution was about $\Delta p_{e,\parallel}=0.01$ a.u. The transverse electron momentum resolution is modulated by the cyclotron motion of the electrons in the magnetic field. At certain time of flights (integer multiples of the inverse cyclotron frequency) the electron transverse momentum is unambiguous due to the properties of the trajectory projection in the magnetic field [6]. Here, the transverse electron momentum cannot be determined. Otherwise, the transverse momentum resolution averages to $\Delta p_{e,\perp}\approx 0.1$ a.u..

Since we did not measure absolute cross sections, our experimental results, reported in Sec. III, were normalized to the calculated total cross section.

B. Theory

In order to theoretically describe helium single ionization we use the continuum distorted wave–eikonal initial state (CDW-EIS) approximation. We also compare in some cases results of the CDW-EIS with those given by the first Born approach. The application of the first Born approximation for exploring atom ionization in projectile-atom collisions has been studied in great detail in the literature (see, e.g., Refs. [7,2] and references therein). The CDW-EIS approximation was introduced in Ref. [8] by replacing the CDW description of the initial state in the CDW-CDW model [9] by its asymptotic (eikonal) form. This approximation belongs to the family of perturbative distorted-wave theories and is rather well documented in the literature (see Refs. [8,10–13] and references therein, and also Ref. [14]). For heavy ion-atom collisions the CDW-EIS has been very successful in describing total ionization cross sections and electron emission spectra. As we noted already in the Introduction (see also Refs. [8,10,2], and references therein) the *n*-*n* interaction is not important for considering ionization cross sections integrated over the projectile scattering angle. The account of this interaction, however, may become of great importance, e.g., for a proper description of ionization cross section differential in the projectile scattering angle [11].

In the present paper, in order to explore the role of the *n*-*n* interaction for helium single ionization by 2-MeV/u C^{6+}, we apply the CDW-EIS approximation with and without taking this interaction into account.

Any theory, which attempts to describe ion-atom collisions, has to deal with the problem which, to some extent artificially, can be split into two main parts: (i) the projectile-target interaction should be properly treated and (ii) (initial and final) free target states should be described with reasonable accuracy.

Concerning the second point, the simplest description of helium states in helium single ionization is to assume that helium has one "active" and one "passive" electron and that the "active" electron can be described as moving in the effective Coulomb field of the atomic core with an effective charge $Z_{t-e}=\sqrt{2I_1}=1.345$, where $I_1=0.9$ a.u. is the first ionization potential of helium. This very simple target description was used in Ref. [16] to perform the study of helium ionization in the Glauber approximation. A good agreement with experiment was reported in Ref. [16].

A slightly more complicated description of the helium consists in approximating the initial state of the active electron by a Hartree-Fock wave function whereas the final electron state is still taken as a continuum one in the Coulomb field of the atomic core with $Z_{t-e}=1.345$ [17]. Although within this description the initial and final target states belong to different Hamiltonians and are not orthogonal, such an approach was used in many papers studying helium single ionization in the CDW-EIS approximation and it had been proven to yield rather good results for spectra of electrons emitted in the process of helium single ionization by the impact of fast singly, multiply, and highly charged ions (e.g., Refs. [18,10,5], see also remark [19]). This target description was also applied for calculations of scattering fast protons by helium targets [11]. The *n*-*n* interaction was assumed in Ref. [11] to be a Coulomb one between the projectile and the target core. Results of Ref. [11] for projectile scattering were in good agreement with the experiment.

Taking into account the above-mentioned points, in the present paper we use the following approximations. First, we regard helium single ionization as an effectively single electron process and assume that in the initial and final states the active target electron moves in the Coulomb field of the target core with a charge $Z_{t-e}=1.345$ [23]. Second, the Coulomb interaction between the projectile and the active electron is considered within the CDW-EIS approach. Third, the residual part of the interaction between the projectile and the target (i.e., the *n*-*n* interaction) is treated as a pure Coulomb interaction between the projectile with a charge Z_p and the net target core charge $Z_{t-p}=1$. Fourth, the *n*-*n* interaction is dealt with in the eikonal approximation. In the latter the distortion due to the *n*-*n* interaction is accounted for by an eikonal factor, representing the asymptotics of the corresponding two-body Coulomb wave, not only in the initial but also in the final channel [11] (see also Ref. [8]). Such an approximation is quite reasonable as long as (i) the projectiles suffer only very small deflections in the collisions and (ii) the velocity of the recoil ion remains negligible compared to that of the emitted electron. Such conditions are, of course, fulfilled for a vast majority of ionizing collisions.

In our first Born calculations we also regard helium single ionization as an effectively single electron process and assume that in the initial and final states the active target electron moves in the Coulomb field of the target core with a charge $Z_{t-e}=1.345$.

Taking into account that a heavy fast projectile suffers very small deflection in the collision and that the velocity of the recoil ion is negligible compared to that of the emitted electron, the basic cross section in our case can be written as

$$\frac{d\sigma^+}{d^3\mathbf{k}_e d^3\mathbf{P}_R d^3\mathbf{q}}=\frac{1}{v_p}|T(\mathbf{q},\mathbf{k}_e)|^2\delta^{(3)}(\mathbf{q}-\mathbf{P}_R-\mathbf{k}_e)\times\delta(\mathbf{v}_p\cdot\mathbf{q}-k_e^2/2-I_1). \quad (1)$$

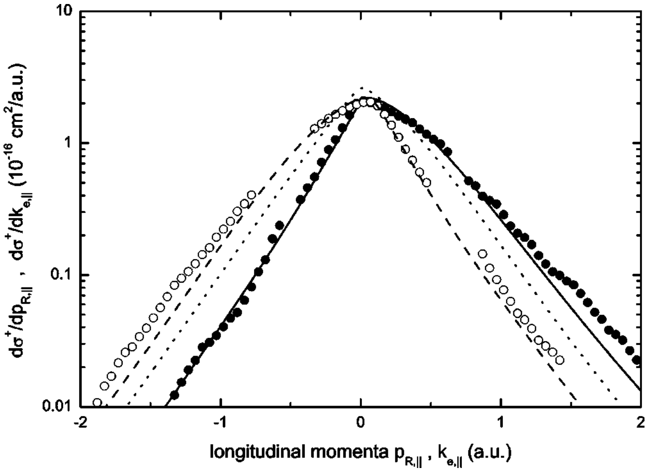

FIG. 1. Longitudinal momentum spectra of electrons and recoil ions in helium single ionization by 2-MeV/u C^{6+}. Solid and open circles: experimental data for electrons and recoil ions, respectively. Solid and dashed curves: CDW-EIS calculations for electrons and recoil ions, respectively. Dotted curve: first Born results for electrons. Both in experiment and calculations only collision events, where emitted electrons had $k_{e,\perp} \leqslant 0.8$ a.u., have been taken into account. Note that in the experimental data we have omitted the momentum regions, where the applied magnetic field is causing a low resolution, as mentioned in the experimental part.

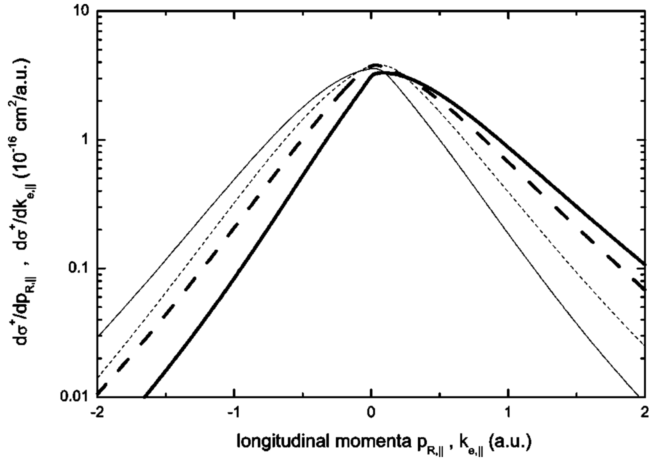

FIG. 2. Longitudinal momentum spectra of electrons and recoil ions in helium single ionization by 2-MeV/u C^{6+}. Thick solid curve: CDW-EIS data for electrons. Thin solid curve: CDW-EIS data for recoil ions. Thick dashed curve: first-order results for electrons. Thin dashed curve: first-order results for recoil ions.

Here $T(\mathbf{q},\mathbf{k}_e)$ is the transition matrix element (calculated in the CDW-EIS or the first Born approximation), $\mathbf{q}$ is the momentum transfer to the target, and $\mathbf{k}_e$ and $\mathbf{P}_R$ are the momenta of the emitted electron and recoil ion, respectively. The three- and one-dimensional δ functions in Eq. (1) arise due to the momentum and energy conservation, respectively, in the collision. The cross section (1) is given in the laboratory frame and it is assumed that the target was initially at rest in this frame.

All calculated cross sections, reported in the following section, have been obtained directly from the basic one, Eq. (1), by means of performing necessary integrations.

III. RESULTS AND DISCUSSION

A. Longitudinal momentum distributions

The study of longitudinal momentum distributions, $d\sigma^+/dk_{e,\|}$ and $d\sigma^+/dp_{R,\|}$, where $k_{e,\|}$ and $p_{R,\|}$ are the components of the momentum $\mathbf{k}_e$ of the emitted electron and of the recoil-ion momentum $\mathbf{P}_R$ which are parallel to the projectile velocity $\mathbf{v}_p$, can provide important information about the collision dynamics and especially about the role of the so-called "postcollision" interaction. In the case of helium single ionization by 2-MeV/u C^{6+} such spectra are displayed in Figs. 1 and 2.

In Fig. 1 we compare our experimental and theoretical (CDW-EIS) results. Here, because of the experimental detection limitations, only those collision events have been counted which were accompanied by the emission of electrons with the transverse momentum $k_{e,\perp} \leqslant 0.8$. The same restriction on the electron transverse momentum was set in the calculation. In Fig. 2, where only theoretical results are shown, electrons with all possible values $k_{e,\perp}$ have been taken into account.

The spectra, presented in Figs. 1 and 2, show remarkable asymmetries for the electrons and recoil ions. A majority of the emitted electrons has a positive longitudinal velocity component, i.e., $\langle k_{e,\|}\rangle > 0$, whereas the recoil ions tend to "prefer" the backwards direction of the motion, $\langle p_{R,\|}\rangle < 0$.

Although there exist many papers, where the longitudinal spectra were considered, we could not locate in the literature any article containing a detailed discussion of all main physical reasons leading to the asymmetries in the longitudinal spectra. For example, quite often (see, e.g., Refs. [24–26]) the origin of the asymmetries is reduced to just the so-called "drag" mechanism. Namely, because of the long-range attractive force between the projectile and the emitted electron the latter is "dragged" in the direction of the projectile motion; on the other hand, the long-range repulsive force between the projectile and the recoil ion pushes the latter backwards. It is clear that in such a picture the sign of the projectile becomes of crucial importance. However, the fact that such a picture is not complete follows, e.g., from experimental results of Ref. [27] where no substantial differences had been found between the longitudinal spectra produced in collisions with protons and antiprotons.

We begin our discussion of the physics laying behind the asymmetries with considering results obtained in the first Born approximation which are also shown in Fig. 2. Although this approximation contains no "postcollision" or "precollision" effect (and, thus, does not include the drag mechanism), it still predicts asymmetries for spectra of both, electrons [28] and recoil ions. According to the first Born approximation the electron spectrum should display quite a strong asymmetry with a main part of ejected electrons moving in the direction of the projectile velocity. First-order results for the recoil-ion distribution also show an asymmetry where, in the case under consideration, more than half of the recoil ions tend to follow the projectiles.

Within the first-order approach the basic reason for the asymmetries is purely kinematical and it is directly connected with the fact that the minimum momentum transfer $q_{min}=(k_e^2/2+I_1)/v_p$ is always positive. ''Absorption'' of this momentum by the target pushes the (center of mass of the) target fragments in the forward direction independently of the sign of the projectile charge.

In a more sophisticated consideration of the collision there appear two more reasons which could also, in principle, lead to asymmetries in the longitudinal spectra. The first is multiple interactions (or virtual-photon exchanges) between the projectile and the target electron which are, in particular, responsible for the ''postcollision'' effect. The second is the *n*-*n* interaction. While the first point has been proven to be of great importance for a proper description of these asymmetries, the *n*-*n* interaction in the case of fast collisions does not seem to noticeably influence the longitudinal distribution even of the recoil ion.

Indeed, in high-velocity collisions electron emission spectra, calculated in the CDW-EIS approach, are not sensitive to whether the *n*-*n* interaction is included into the consideration or not. In general, such a statement cannot be made for the recoil-ion distributions. However, the energy conservation, being applied to a collision of a fast heavy particle and an atom, leads to the result that the momentum conservation in the longitudinal directions is expressed via the characteristics of just the target (and its final fragments): $k_{e,\parallel}+p_{R,\parallel}=(k_e^2/2+I_1)/v_p$. This equality, in fact, binds so strongly the longitudinal momentum distribution of the emitted electron and that of the recoil ion that the latter can be expressed via the former [30]. Therefore, taking into account that the electron distribution is practically not influenced by the *n*-*n* interaction, one can draw a conclusion that the effect of the *n*-*n* interaction on the longitudinal distribution of the recoil ions is also negligible.

The above conclusion is consistent with a simple semiclassical picture of the interaction between a fast projectile and an atomic core. Let us assume that the projectile moves along a classical trajectory and the target core initially rests at the origin. Collision impact parameters which are of importance for helium ionization are not much smaller than 1 a.u. It is clear that in such collisions the projectile trajectory can be very well approximated by a straight line and that the target core, because of its very large mass (compared to that of the electron), can acquire only a negligibly small velocity. Taking this into account, it is not difficult to see that in the longitudinal direction the overall effect of the projectile on the motion of the target core is close to zero because the projectile actions on the incoming and outgoing parts of the projectile trajectory nearly compensate each other. Note that the above discussed compensation is substantially less complete in the case of the interaction between the projectile and the target electron. This is because the electron is bound initially and is free finally and a typical electron velocity is much larger than that of the target core.

One more point, which is rather obvious, is that the interaction between the active electron and the target core is also very important for the asymmetries to occur. In the case of projectile scattering on a free electron the corresponding (Rutherford) cross section is independent of the sign of the projectile charge. Therefore, the presence of the ''third'' body is certainly necessary in order to explain the differences in the longitudinal spectra of electrons emitted in collisions with negatively and positively charged projectiles [31].

Summarizing the above discussion the main reasons for the asymmetries in the longitudinal spectra can be outlined as follows. The asymmetry in the electron longitudinal spectrum is caused by the interplay between the following three factors: (i) the collision kinematics ($q_{min}>0$), (ii) the ''postcollision'' interaction of the electron with the projectile, and (iii) the electron interaction with the target core. Exactly the same factors are responsible also for the asymmetry in the longitudinal spectrum of the recoil ions. Due to the momentum-energy conservation in the collision one has $p_{R,\parallel}=(k_e^2/2+I_1)/v_p-k_e\cos(\vartheta_e)$, where ϑ_e is the angle between the electron and the projectile velocities. The ''postcollision'' interaction between the electron and the projectile changes the angular distribution of the emitted electron with respect to the first Born predictions. Since for a given k_e the minimum momentum transfer is fixed, the longitudinal recoil momentum has to ''adapt'' to a new direction of the motion of the emitted electron. Thus, the interaction between the projectile and the electron indirectly but very effectively influences the longitudinal momentum distribution of the recoil ion whereas the *n*-*n* interaction, which directly couples the projectile and the target core, turns out to be of negligible importance.

B. Transverse momentum distributions

In the plane perpendicular to the projectile velocity (the transverse directions) the restrictions imposed by the energy-momentum conservation are not so strong as in the longitudinal direction. In addition, a semiclassical consideration of the collision process shows that in the transverse direction the overall action of the projectile on the target core can result in a substantial exchange of momentum that is in a sharp contrast to the situation discussed above. Therefore, the study of transverse spectra of electrons, recoil ions, and projectiles can unveil important information, especially about that part of the collision dynamics which is ''hidden'' when considering the longitudinal spectra.

In Fig. 3 we display our experimental and theoretical results for the transverse spectrum, $d\sigma^+/dk_{e,\perp}$, of the emitted electron. As we noted already, the *n*-*n* interaction does not influence the electronic spectrum. In addition, since the difference between the CDW-EIS and first-order results for the transverse spectrum is much weaker than for the longitudinal one, one can conclude that multiple photon exchanges between the projectile and the target electron are not very important in this case.

As one could expect, the role of the *n*-*n* interaction in the collision dynamics starts to unveil itself when considering transverse distributions of the heavy particles.

In Fig. 4 results for the projectile scattering $d\sigma^+/dq_\perp$ are shown. Both in experimental and theoretical data only those collision events have been taken into account where the projectile scattering is accompanied by emission of electrons

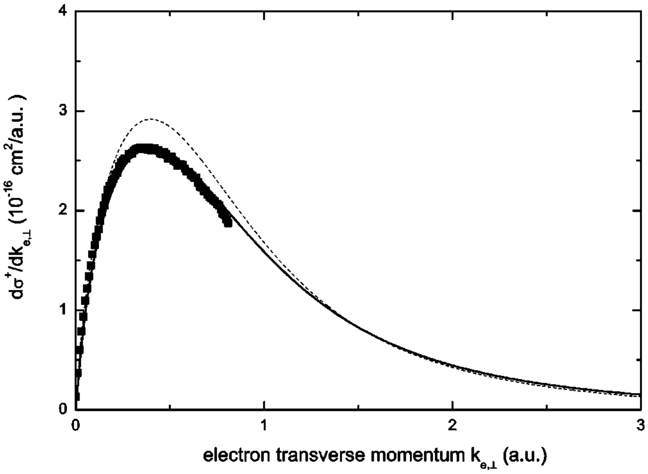

FIG. 3. Transverse momentum spectrum of electrons in helium single ionization by 2-MeV/u C^{6+}. Squares: experimental data. Solid curve: CDW-EIS calculation. Dashed curve: first-order calculation.

with energies $\leqslant 9$ eV. It is seen that the inclusion of the *n*-*n* interaction into CDW-EIS calculations substantially changes the absolute values and the shape of the calculated cross section for the projectile scattering and brings it into much better overall agreement with the experimental data.

As it follows from the calculations shown in Fig. 4, the whole range of $q_\perp$ under consideration can be subdivided into three parts where the *n*-*n* interaction influences the cross section in a different way. In the ranges of "small" ($q_\perp \lesssim 0.5$) and "large" ($q_\perp \gtrsim 2.5$) transverse momenta the inclusion of the *n*-*n* interaction increases calculated cross section

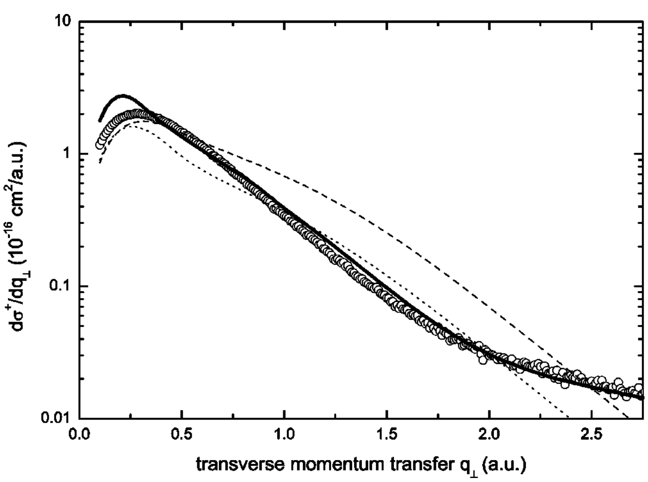

FIG. 4. Transverse momentum spectrum of the projectile in helium single ionization by 2-MeV/u C^{6+}. Circles: experimental data. Solid curve: result of the CDW-EIS approximation with inclusion of the *n*-*n* interaction. Dashed curve: result of the CDW-EIS approximation without inclusion of the *n*-*n* interaction. Dotted curve: results of the first-order approximation. Both in the experimental and theoretical data only collision events with electron emission energies $\leqslant 9$ eV have been taken into account. All the theoretical data have been convoluted with the estimated experimental resolution of 0.3 a.u.

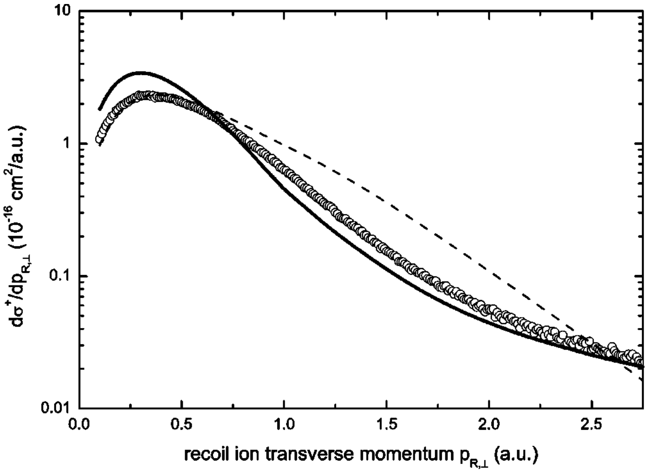

FIG. 5. Transverse momentum spectrum of the recoil ions in helium single ionization by 2-MeV/u C^{6+}. Circles: experimental data. Solid curve: result of the CDW-EIS approximation with inclusion of the *n*-*n* interaction. Dashed curve: result of the CDW-EIS approximation without inclusion of the *n*-*n* interaction. Both in the experimental and theoretical data only collision events with $k_{e,\perp} \leqslant 0.8$ have been taken into account. All the theoretical data have been convoluted with the estimated experimental resolution of 0.3 a.u.

values. In contrast, for the "intermediate" $q_\perp$ ($0.5 \lesssim q_\perp \lesssim 2.5$) this interaction reduces the cross section.

The effect of the *n*-*n* interaction on the calculated cross section at small $q_\perp$ could be understood in terms of the following simple picture. First, when the *n*-*n* interaction is included the projectile "sees" a neutral target. Second, scattering with small momentum transfers generally correspond to collisions with large impact parameters. Third, for these impact parameters the net influence of the neutral target on the projectile is very small. This results in the enhancement of the projectile scattering into small angles compared to the case where the *n*-*n* interaction is "switched off" and the projectile is always affected by the long-range Coulomb field of the active target electron.

Concerning projectile scattering with large momentum transfers it is plausible to assume that such a scattering becomes more effective when the heavy target core can directly interact with the projectile, i.e., when the *n*-*n* interaction is not switched off.

The physical reasons for the decreasing effect of the *n*-*n* interaction at the range of intermediate $q_\perp$ are not quite clear. Formally, this decreasing effect can be understood as follows. The total number of ionization events is not influenced by the *n*-*n* interaction. Therefore, both calculations, with and without including the *n*-*n* interaction, yield identical results for the total cross section. It means that if there are some ranges of $q_\perp$, where the inclusion of the *n*-*n* interaction into calculations increases the differential cross section $d\sigma^+/dq_\perp$, then there also has to be a range (or ranges) of $q_\perp$, where the *n*-*n* interaction decreases this cross section.

In Fig. 4 we also show results of the first Born approximation in which neither the *n*-*n* interaction nor multiple-photon exchanges between the projectile and the electron are taken into account. By comparing the first-order results with those obtained within the CDW-EIS approach one can draw the conclusion that not only the *n*-*n* interaction but also the multiple photon exchanges are of importance for a proper description of the projectile scattering.

In Fig. 5 we display results for the transverse spectrum of the recoil ions, $d\sigma^+/dp_{R,\perp}$. Since in the experiments only those events were detected, where the transverse and longitudinal electron momenta were restricted to $k_{e,\perp}<0.8$ (that roughly corresponds to including electrons with $\varepsilon_k \leqslant 9$ eV), the same condition for $k_{e,\perp}$ has been set in our calculations. CDW-EIS calculations were done by including and neglecting the *n*-*n* interaction. As it follows from the calculations, the *n*-*n* interaction strongly influences the recoil transverse distribution. Inclusion of this interaction into account brings the calculated results substantially closer to the experimental data, except for the range of rather small $p_{R,\perp}$.

As in the case with the cross section $d\sigma^+/dq_\perp$ we observe for the transverse momentum distribution of the recoil ions that the whole range of $p_{R,\perp}$ can also be split into subranges with small, intermediate, and large transverse momentum transfers where the effects of the *n*-*n* interaction on the recoil distribution are similar to those caused by this interaction for the projectile.

IV. CONCLUSIONS

We have investigated three-particle momentum transfer in helium single ionization by 2-MeV/u C^{6+}. By comparing experimental data with calculations we have displayed clear signatures of the *n*-*n* interaction in the transverse distributions of the recoil ion and projectile. This interaction has been shown to represent an important mechanism for the momentum exchange in ionizing collisions.

We have also discussed in some detail the mechanisms leading to the forward-backward asymmetry in the longitudinal spectra of the emitted electrons and recoil ions. These mechanisms are (i) the collision kinematics ($q_{min}>0$); (ii) the higher-order contributions in the projectile-electron interaction; and (iii) the electron interaction with the target core. These mechanisms are identical for both the electron and the recoil-ion asymmetries. In contrast to the transverse direction(s) the *n*-*n* interaction plays practically no role in the longitudinal direction.

ACKNOWLEDGMENT

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[4] We note that similar collision systems (1- and 2.5-MeV/u C^{6+} + He) were considered in Ref. [5] where energy and angular distributions of emission from helium were explored. The present study could, to some extent, be viewed as complementary to those performed in Ref. [5].

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