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Projectile-target core interaction in single ionization of helium by 100-MeV/u C^{6+} and 1-GeV/u U^{92+} ions

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We consider single ionization of helium by very fast highly charged ions. The ionization is treated as a three-body problem which involves the "active" target electron, the target core (consisting of the target nucleus and the "passive" target electron) and the projectile ion. In contrast to the previous studies of this process, in which the interaction between the projectile and the target core was treated as a purely Coulomb one, we describe this interaction using the same core potential which acts on the active electron and which has both Coulomb and short-range parts. According to our results the deviation of the interaction between the projectile and the target core from the purely Coulomb law has on overall a weak effect on the ionization dynamics. In particular, we show that the account of this deviation does not enable one to get any better agreement with experimental data on the fully differential cross section for the electron emission into the so-called perpendicular plane.

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I. INTRODUCTION

Collisions of fast highly charged ions with helium represent an interesting example of quantum dynamical few-body systems [1]. During the last several years single ionization of helium has attracted a lot of attention, both experimental and theoretical [2–10].

The most detailed information on the process of ionization is obtained by exploring the collision dynamics on the level of the fully differential cross section (FDCS). The parameter $\eta_p = Z_p / v_p$, where Z_p is the projectile charge and v_p is the collision velocity, is commonly used to characterize the effective strength of the projectile-target interaction. At small values of η_p ($\eta_p \ll 1$), where the projectile-target interaction is weak, one normally expects that already the first-order Born approximation should yield a reasonable description of the collisions.

However, such expectations have been put into question by experimental results on single ionization of helium by 100-MeV/u C^{6+} projectiles. At this impact energy the collision velocity is quite high ($v_p = 58$ a.u.) leading to the collision strength parameter η_p of just about 0.1. Nevertheless, large discrepancies were found between the experimental data and the first Born results for the electron emission outside the scattering plane [11]. At the same time, for the electrons emitted into the scattering plane the experimental FDCS was reasonably well reproduced by the first Born theory [2].

It was suggested in [3] that the discrepancies might have their origin in the interaction between the projectile and the target core (the target nucleus and the passive atomic electron). According to the first Born approximation, this interaction does not influence the ionization transition amplitude. Therefore, a number of theoretical models including, in particular, the second Born, the Glauber, the continuum-distorted-wave–eikonal-initial-state (CDW-EIS), and the symmetric-eikonal approximations were applied to study the electron emission. All these models go beyond the first Born approximation and, in particular, suggest that the interaction between the projectile and the target core does influence the shape of the FDCS.

These models predicted noticeable deviations in the electron emission pattern from the first Born results, especially outside the scattering plane [12]. It also should be noted that in the case of the ionization by 100-MeV/u C^{6+} ions the predictions of these models concerning the character of the deviations and their magnitude were quite similar [12]. In particular, according to all of these models the main reason for the deviations in the FDCS from the first Born results in this case is the interaction between the projectile and the target core.

These models, however, did not enable one to get any better overall agreement with the experiment [3]. Moreover, for the FDCS for the electrons emitted into the plane, perpendicular to the transverse momentum transfer (the perpendicular plane), they all predicted a minimum exactly there where, according to the experiment, a maximum should be. Since for this plane the first Born approximation predicts almost a constant value for the emission pattern (see also Fig. 3) [13], the disagreement between the experiment and theory actually had became even worse.

It was then suggested [9] that the difference between the experiment and theory is not a signature of any principal shortcoming of the atomic collision models but is simply caused by the thermal motion of the target atoms. Because of this motion a detection of the final momentum of the recoil ion does not allow one to get precise information about the value and direction of the momentum transfer in the collision. As a result, the orientation of the perpendicular plane becomes experimentally not very well defined and the measured emission into this plane can contain noticeable admixtures of the emission into other planes, including "traces" of the (relatively very large) binary peak from the scattering plane.

The role of possible experimental uncertainties was later studied in [10]. It was confirmed that a nonzero temperature of the target gas indeed results in the appearance of a maximum in the emission spectra exactly there where it was observed in the experiment. Besides, the authors of [10] found out that the size of the projectile beam also contributes to the appearance of the maximum. Nevertheless, the question has not been settled, in particular, because the above two effects seem to be insufficient in order to fully explain the difference between the experimental data and theoretical results.

In another recent paper [14] it was suggested that the reason for the discrepancies could lie in the fact that in the theoretical models, used so far to describe this process, the interaction between the projectile and the target core was taken as a pure Coulomb interaction between two pointlike charges: Z_p and 1 for the projectile and target core, respectively. Strictly speaking such an approximation is only valid for collisions with impact parameters much larger than the size of a helium atom. If a substantial part of the electron emission arises in collisions, in which the projectile penetrates the target core, the above theoretical models might be not able to yield a satisfactory description of the ionization process. A similar suggestion has been also made in [15].

In the present paper we pursue a rather modest goal [16]. Namely, taking into account what has been said in the above paragraph, we shall attempt to find out whether the account of a non-Coulomb part of the interaction between the projectile and the target core could bring substantial changes into the form of calculated cross sections and, in particular, whether this account can improve the description of the experimental data on single ionization of helium by 100-MeV/u C^{6+} projectiles. Besides, for a comparison we shall also consider single ionization of helium by 1-GeV/u U^{92+} ions. In the latter case the collision velocity is even by a factor of 2 higher ($v_p=120$ a.u.) but the parameter $\eta_p=Z_p/v_p$ is rather close to 1 ($\eta_p=0.77$).

Our consideration of both these collision systems is based on a distorted-wave model. This model will be described in Sec. II and here we just mention that it represents the first term of a distorted-wave expansion with the expansion parameter roughly given by Z_p/v_p^2. This expansion parameter is to be compared with the corresponding expansion parameter Z_p/v_p of the Born approximation. Atomic units are used throughout except where otherwise stated.

II. THEORETICAL MODEL

Following the previous works on single ionization of helium by fast ions we shall treat this process by considering its three-body model. This model involves (1) the active target electron, (2) the target core, and (3) the projectile. The projectile and the active electron interact via the (relativistic) Coulomb force. The target core consisting of the target nucleus and the passive electron is supposed to behave in the collision as a rigid body whose internal structure is not changed by the collision.

It is well known that even in collisions at relativistic impact velocities the majority of electrons emitted from such a light target such as helium have velocities with respect to the target recoil ion which do not exceed a few atomic units. Therefore, we shall consider the ionization using the rest frame of the target nucleus and describe the active electron nonrelativistically.

In this frame the field of the target core acting on the active electron and the projectile is described by a scalar potential. This potential is taken to be the same for the active electron and the projectile (as well as for the initial and final collision channels) and is approximated by

$$\Phi(\xi)=\frac{1}{\xi}+(1+\beta\xi)\frac{\exp(-\alpha\xi)}{\xi}. \qquad (1)$$

Here ξ refers to the distance measured from the center of the target core (i.e., from the target nucleus) and is given in the target frame. In accordance with results of [17] the values of the parameters α and β were chosen to be 3.36 and 1.665 a.u., respectively.

The initial state of the colliding system is taken as a product of unperturbed states of the projectile and target electron multiplied by eikonal factors. These factors reflect the distortion of the initial state caused by the Coulomb interaction between the projectile and the active electron and by the interaction between the projectile and the target core which consists of the Coulomb and short-range parts.

The final state is represented by a product where the interaction between the projectile and the target core is approximated by corresponding eikonal phase (which accounts for both the Coulomb and short-range parts of this interaction). The distortion for the projectile-active electron subsystem in the final state, in the spirit of the CDW-EIS approach [18], is modeled by a (relativistic) continuum-distorted-wave factor.

The initial and final unperturbed states of the electron moving in the field of the target core are obtained by a numerical solution of the corresponding Schrödinger equation. Thus, our model is in essence the well-known continuum-distorted-wave–eikonal-initial-state approximation [18] in which the interaction between the projectile and the target core in the initial and final channels is incorporated via the corresponding eikonal phase factors and care is taken in order to account for relativistic effects in the projectile-target motion. For brevity below we shall denote this model as rCDW-EIS.

The main difference between the approach of the present paper and the previous attempts [7,8] to address the problem of helium single ionization by very fast ions is that the interaction between the projectile and the target core, in addition to the Coulomb part, involves also the short-range interaction [see Eq. (1)]. Besides, an eikonal-like description of the projectile-active electron coupling in the final channel has now been replaced with the (relativistic) continuum-wave Coulomb distortion factor. The latter is taken in such a way as to account for the necessary relativistic changes appearing in the form of the Coulomb field generated by a very fast moving ion in the rest frame of the target.

It is important to remember that, as was already mentioned, the model described above, being in essence the continuum-distorted-wave–eikonal-initial-state approximation, represents the first term of the corresponding distorted-wave expansion. In this expansion, in contrast to the Born approximation, the expansion parameter is given by Z_p/v_p^2 (instead of the Born expansion parameter Z_p/v_p). This permits one to use this model as long as the condition

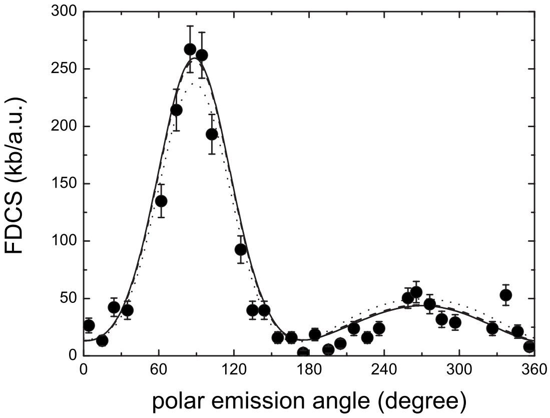

FIG. 1. The FDCS for single ionization of helium by 100-MeV/u C^{6+} projectiles plotted as a function of the polar emission angle. The cross section is given in the scattering plane. The electron emission energy $\varepsilon_k = 6.5$ eV and the total momentum transfer $q = 0.65$ a.u. Symbols: experimental data from [2]. Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dashed curve: the projectile-target core interaction is modeled by the Coulomb part of Eq. (1) only. Dotted curve: the first Born results.

$Z_p/v_p^2 \ll 1$ is fulfilled, which may be the case even if the projectile-target interaction is so strong, $Z_p/v_p \gtrsim 1$, that the first Born approximation would already strongly fail.

The first-order (Born) limit of the present three-body model is obtained if all the distortion factors are set to unity. In particular, within the first-order approach the interaction between the projectile and the target core completely drops out from the transition amplitude. Besides, the interaction between the projectile and the active target electron is reduced just to a single-photon exchange.

III. RESULTS AND DISCUSSION

A. Fully differential cross section

Let us now turn to considering the FDCS for single ionization of helium, $\frac{d\sigma^+}{d^2\mathbf{Q}d^3\mathbf{k}}$. Here, $\mathbf{Q}$ is the transverse part of the total momentum transfer to the target which is given by $\mathbf{q} = (\mathbf{Q}, q_{\min})$, where $q_{\min} = (\varepsilon_k - \varepsilon_0)/v_p$ with ε_0 and ε_k being the initial and final energies of the active electron. $\mathbf{k}$ is the momentum of the emitted electron with respect to the target nucleus. We shall first consider the ionization caused by 100-MeV/u C^{6+} projectiles ($Z_p/v_p \simeq 0.1$ and $Z_p/v_p^2 \simeq 1.7 \times 10^{-3}$).

In Figs. 1 and 2 we show the FDCS for the scattering plane. This plane is defined by the condition $\varphi_k = 0°$, where the azimuthal angle φ_k of the momentum $\mathbf{k}$ of the emitted electron is counted from the direction of the transverse momentum transfer $\mathbf{Q}$. This cross section is given as a function of the polar angle, $\vartheta_{\mathbf{k}} = \arccos(\mathbf{k} \cdot \mathbf{v}_p / k v_p)$, of the momentum of the emitted electron for fixed emission energy and momentum transfer. The results are on an absolute scale.

We observe in these figures familiar structures: at the lower momentum transfer (see Fig. 1) the emission pattern clearly exhibits the so-called binary and recoil peaks; at higher momentum (see Fig. 2) the recoil peak practically disappears. It is also seen in these figures that, while the inclusion of the interaction between the projectile and the target core has a visible (although rather weak) impact on the calculated cross section, the latter is practically insensitive to whether this interaction is approximated by merely the Coulomb part of the scalar potential (1) or by the full expression (1).

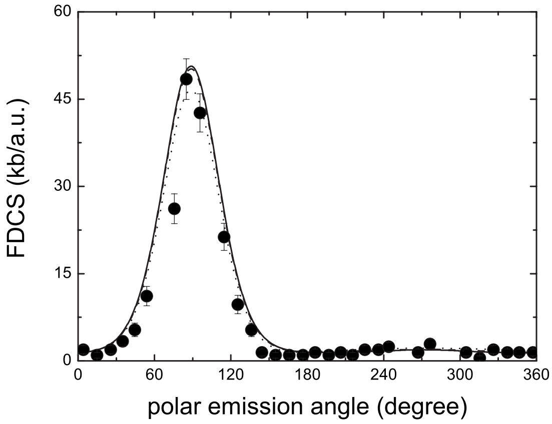

FIG. 2. Same as in Fig. 1 but for the electron emission energy of 17.5 eV and the total momentum transfer of 1.43 a.u.

The situation becomes somewhat different if we consider the emission into the perpendicular plane (see Fig. 3). The latter is defined by the condition $\varphi_k = 90°$. The emission into this plane is very weak and much more sensitive to the details of a theoretical description. For this plane the deviations between the results calculated in the different approximations become more pronounced. In this plane the higher-order contributions in the interaction between the projectile and the active electron change the shape of the cross section. The inclusion of the interaction between the projectile and the target core brings further quite noticeable changes into the calculated emission pattern. Moreover, in the perpendicular plane we also observe that there is a visible effect in the

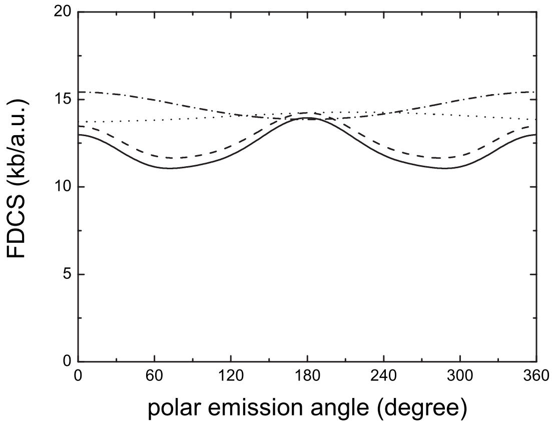

FIG. 3. Same as in Fig. 1 but the cross section is given in the perpendicular plane. Besides, the dashed-dotted curve displays results of the calculation in which the interaction between the projectile and the active electron is described within the rCDW-EIS but the projectile-target core interaction is completely ignored.

emission spectrum caused by the short-range part of this interaction.

However, in contrast to the experimental data showing a pronounced maximum at $\vartheta_k \sim 90°$ and 270° (see, e.g., [10]), the inclusion of the interaction between the projectile and the target core results in a minimum in the calculated emission spectrum. Moreover, this minimum becomes even slightly deeper if the short-range part of this interaction in taken into account. Thus, the present model is unable to explain the appearance of the maximum at $\vartheta_k \simeq 90°$ observed in the experimental data.

At this point it might be appropriate to comment briefly on a recent paper [15]. In that paper an attempt was made to take into account the interaction between the projectile and the target core by a convolution of results of the first Born approximation for the FDCS with classical elastic scattering of the projectile on the target core using a Monte Carlo event generator technique. The authors reported that they were able to reproduce qualitatively the FDCS for the emission into the perpendicular plane.

The approach of [15] is based on the assumption that the elastic collision between the projectile and the target core with a well-defined value of the impact parameter is characterized by a well-defined value of the momentum transfer and that the correspondence between these two quantities is given in accordance with classical mechanics. However, as is well known, such an assumption might be valid only provided the condition $2Z_pZ_t/v \gg 1$ is fulfilled, where Z_t is the (effective) charge of the target core. In the case of helium ionization by 100-MeV/u C^{6+} ions, $2Z_pZ_t/v \ll 1$, the scattering is not classical and there is no classical correspondence between the momentum transfer and the impact parameter (moreover, strictly speaking the latter quantity even hardly has physical significance).

Besides, the consideration of [15] predicts results that do not depend on the sign of the projectile charge. However, at small values of the parameter η_p, $\eta_p = Z_p/v_p \ll 1$, where the Born series represents a sensible expansion for the transition amplitude, this amplitude can be approximated as $a \simeq c_1 Z_p + c_2 Z_p^2$, where $c_1 \neq 0$ and $c_2 \neq 0$ are independent of Z_p. As a result, the corresponding cross section will contain terms proportional to Z_p^2 and Z_p^3 and, therefore, will be dependent on the sign of Z_p. Note that this simple qualitative argumentation is fully supported by calculations performed in [12].

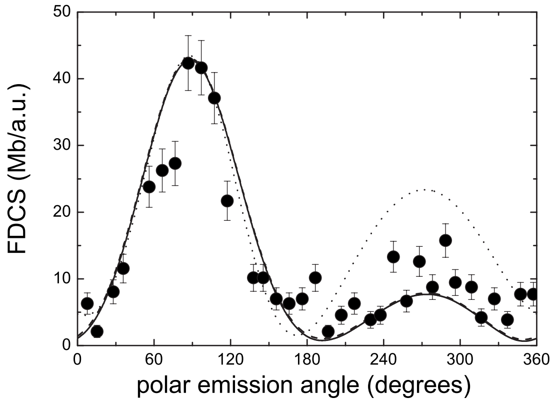

FIG. 4. The FDCS for single ionization of helium by 1-GeV/u U^{92+} projectiles plotted as a function of the polar emission angle. The cross section is given in the scattering plane. The electron emission energy $\varepsilon_k = 2$ eV and the total momentum transfer $q = 0.65$ a.u. Symbols: experimental data from [7]; these data have been fit to the maximum of the solid curve. Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dashed curve: the projectile-target core interaction is modeled by the Coulomb part of Eq. (1) only. Dotted curve: the first Born results.

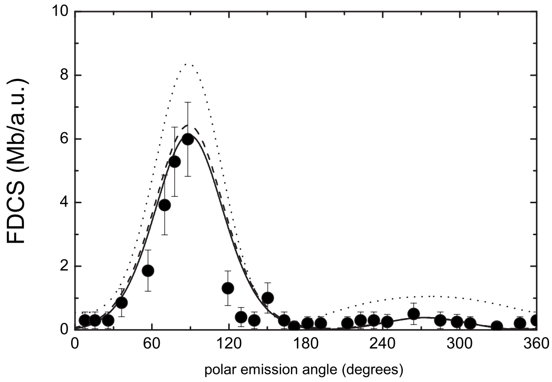

FIG. 5. Same as in Fig. 4 but for the electron emission energy of 10 eV and the total momentum transfer of 1 a.u.

Taking into account what has been said in the previous two paragraphs one sees that the model presented in [15] may not be applied to collisions when $Z_pZ_t/v \ll 1$ and, therefore, does not allow one to draw any solid conclusions on the physical mechanisms responsible for the shape of the measured cross section.

Let us now turn to the FDCS in collisions with 1-GeV/u U^{92+} projectiles. Note that in this case the Born expansion parameter is already rather large $(Z_p/v_p \simeq 0.77)$ but the distorted-wave expansion parameter remains still much less than 1 $(Z_p/v_p^2 \simeq 6 \times 10^{-3})$.

In Figs. 4 and 5 we plot the FDCS for the scattering plane as a function of the polar angle of the emitted electron. Theoretical results shown in these figures are on an absolute scale. The experimental data are normalized (at the cross-

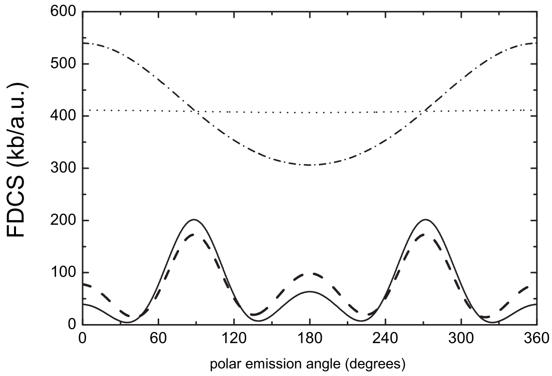

FIG. 6. Same as in Fig. 5 but the cross section is given in the perpendicular plane. Besides, the dashed-dotted curve displays results of the calculation in which the interaction between the projectile and the active electron is described within the rCDW-EIS but the projectile-target core interaction is completely ignored.

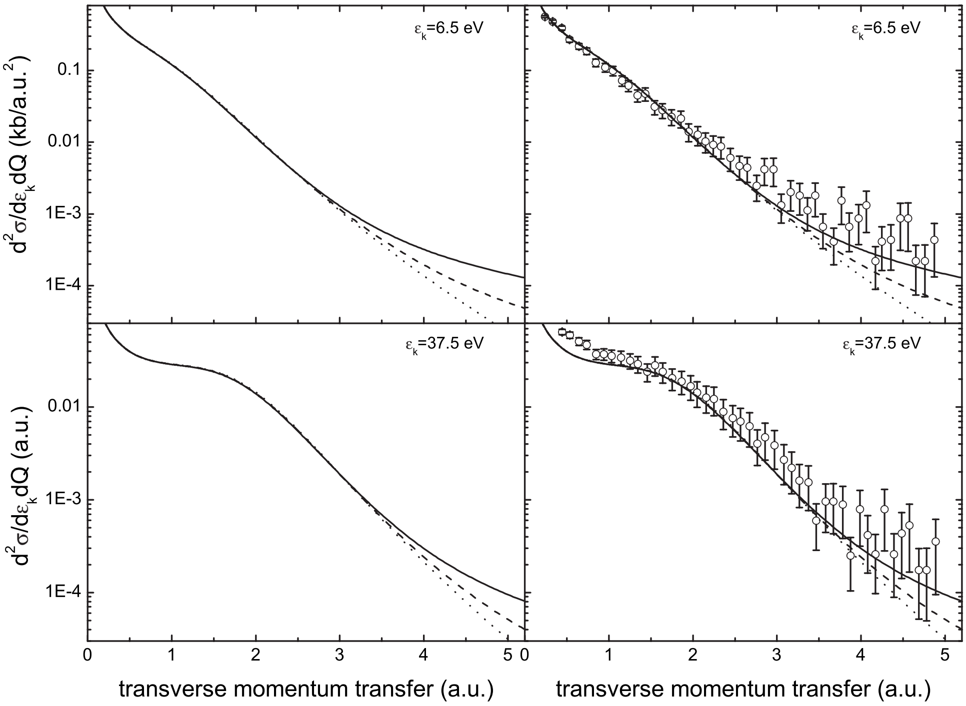

FIG. 7. The doubly differential cross section $d^2\sigma/d\varepsilon_k dQ$ for single ionization of helium by 100-MeV/u C^{6+} projectiles given as a function of the transverse momentum transfer Q at a fixed value of the emission energy (ε_k $=6.5$ and $\varepsilon_k=37.5$ eV for the upper and lower panels, respectively, of the figure). Left panels of the figure: solid curves are results obtained by including into the interaction between the projectile and the target core the full expression (1); dashed curves show the results obtained when the projectile-target core interaction is modeled by the Coulomb part of Eq. (1) only; dotted curves are the first Born results. Right panels: the same as in the left panels plus experimental data from [2].

section maximum) to those theoretical results which are obtained with the inclusion of the full interaction between the projectile and the target core.

As in the previous case, the main feature of the emission pattern is the presence of the binary and recoil peaks. However, in contrast to the case of helium ionization by 100-MeV/u C^{6+} ions, the calculated cross section in collisions with the 1-GeV/u uranium ions substantially depends on whether or not the interaction between the projectile and the target core is taken into account. The effect of the short-range part of this interaction also becomes somewhat more visible. Nevertheless, for the collision parameters considered in Figs. 4 and 5, the calculated spectrum of the electron emission into the scattering plane still changes very little when the short-range part of potential (1) is taken into account.

Results for the electron emission into the perpendicular plane are shown in Fig. 6. As in the case with the carbon projectiles, the calculated FDCS for the emission into this plane turns out to be much more sensitive to the approximations used. In particular, the inclusion of the interaction between the projectile and the target core substantially reduces the magnitude of the calculated cross section and has a very strong impact on its shape. Besides, the inclusion of the short-range part of potential (1) into this interaction results in a more pronounced effect. One more interesting feature of the emission pattern shown in Fig. 6 is that the maximum in the emission is situated now at $\simeq 90°$ and not at $0°$ (or $180°$) as it was in the case with the carbon projectiles. This finding is in agreement with the earlier results of [12,19] suggesting that, when the effective strength of the projectile field increases, a minimum in the calculated cross section at $\simeq 90^0$ disappears and, instead, the cross section attains a maximum at this point.

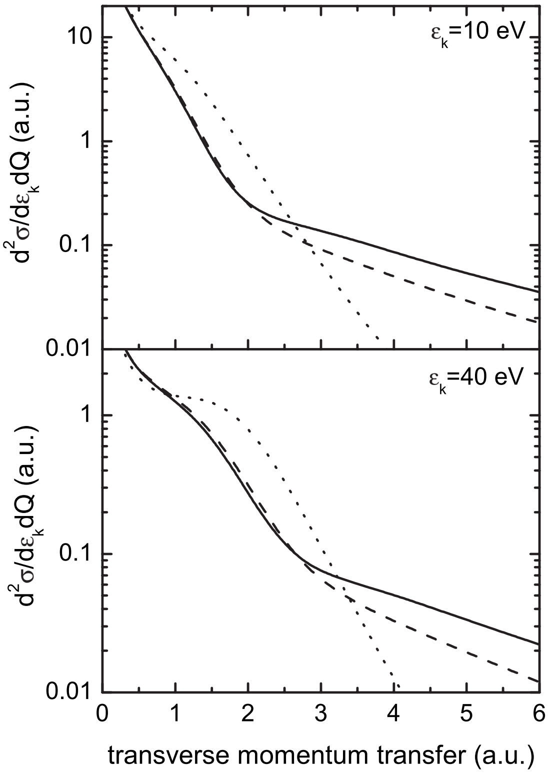

FIG. 8. The doubly differential cross section $d^2\sigma/d\varepsilon_k dQ$ for single ionization of helium by 1-GeV/u U^{92+} projectiles given as a function of the transverse momentum transfer Q at a fixed value of the emission energy ($\varepsilon_k=10$ and $\varepsilon_k=40$ eV for the upper and lower panels, respectively, of the figure). Solid curve: results obtained by including into the interaction between the projectile and the target core the full expression (1). Dashed curve: the projectile-target core interaction is modeled by the Coulomb part of Eq. (1) only. Dotted curve: the first Born results.

B. Cross-section differential in the emission energy and transverse momentum transfer

The influence of the interaction between the projectile and the target core on the dynamics of single ionization of helium in general depends not only on the electron emission energy, the momentum transfer, and the magnitude of the parameter η_p but also on a plane chosen to observe the FDCS. In order to get some more "integral" ideas about the influence of the projectile-target core interaction as well as of the importance of its Coulomb and short-range parts on the collision process we shall now consider the ionization cross-section differential in the emission energy and the transverse part of the momentum transfer, $d^2\sigma^{(+)}/dQd\varepsilon_k$. Such a cross section is shown in Figs. 7 and 8 where it is considered as a function of the transverse momentum Q at fixed values of the emission energy ε_k.

In the case of single ionization of helium by 100-MeV/u C^{6+} projectiles noticeable differences in the cross section calculated without and with including the interaction between the projectile and the target core begin starting with $Q \simeq 3-4$ a.u. (see Fig. 7). In this figure we also see that at about the same values of Q the short-range part of this interaction begins to have a visible effect on the cross section. This effect increases with increasing Q and changes the cross section by about a factor of 2 at $Q \simeq 5$ a.u.

Compared to collisions with the carbon ions, the dynamics of single ionization of helium by 1-GeV/u U^{92+} projectiles is much stronger affected by the interaction between the projectile and the target core which is clearly seen in Fig. 8. Now the differences in the calculated cross sections caused by this interaction start already at $Q \simeq 0.5$ a.u. Besides, the effect of the short-range part of this interaction becomes noticeable at $Q \simeq 2-3$ a.u. and, thus, also comes into play at comparatively smaller values of Q.

IV. CONCLUSIONS

We have considered some aspects of single ionization of helium by very fast highly charged nuclei. In this consideration we concentrated on the effects on the dynamics of this process caused by the interaction between the projectile nuclei and the helium core and we were especially interested in the role played by the short-range part of this interaction. As one could expect the role of this interaction as well as that of its short-range part was found to increase when the transverse momentum transfer increases. It was also shown that they may result in very substantial effects. In particular, the inclusion of this interaction in form (1) enables one to get a better description of the experimental data of [2] on the doubly differential ionization cross section at larger values of Q.

However, at smaller values of Q, for which the experimental data on the fully differential cross sections are available, our consideration shows that the short-range part of this interaction, both in collisions with 100-MeV/u C^{6+} and 1-GeV/u U^{92+} projectiles, has a very weak influence on the form and absolute values of the fully and doubly differential cross sections. Thus, our present study does not support the idea expressed in [14,15] that the neglect of the short-range part of this interaction in the previous theoretical models could be responsible for the very substantial deviations between the experiment and theory in the case of the electron emission into the perpendicular plane.

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[1] *Many-Particle Quantum Dynamics in Atomic and Molecular Fragmentation*, edited by J. Ullrich and V. P. Shevelko (Springer-Verlag, Berlin, 2003).

[2] D. Madison *et al.*, J. Phys. B **35**, 3297 (2002).

[3] M. Schulz *et al.*, Nature (London) **422**, 48 (2003).

[4] D. H. Madison, D. Fischer, M. Foster, M. Schulz, R. Moshammer, S. Jones, and J. Ullrich, Phys. Rev. Lett. **91**, 253201 (2003).

[5] D. Fischer, A. B. Voitkiv, R. Moshammer, and J. Ullrich, Phys. Rev. A **68**, 032709 (2003).

[6] M. Foster *et al.*, J. Phys. B **37**, 1565 (2004).

[7] A. B. Voitkiv, B. Najjari, R. Moshammer, M. Schulz, and J. Ullrich, J. Phys. B **37**, L365 (2004).

[8] A. B. Voitkiv and B. Najjari, J. Phys. B **37**, 4831 (2004).

[9] J. Fiol, S. Otranto, and R. E. Olson, J. Phys. B **39**, L285 (2006).

[10] M. Dürr, B. Najjari, M. Schulz, A. Dorn, R. Moshammer, A. B. Voitkiv, and J. Ullrich, Phys. Rev. A **75**, 062708 (2007).

[11] The scattering plane is a plane spanned by the vectors of the initial and final projectile momenta.

[12] A. B. Voitkiv, B. Najjari, and J. Ullrich, J. Phys. B **36**, 2591 (2003).

[13] According to the first Born approximation the electron emission pattern should be a constant in the plane, which is perpendicular to the vector of the total momentum transfer. However, under the conditions of the experiment [3], because of high collision velocity, the minimum momentum transfer was very small and the transverse part of the momentum transfer practically coincided with the total momentum transfer.

[14] M. Foster, J. L. Peacher, M. Schulz, D. H. Madison, Z. Chen, and H. R. J. Walters, Phys. Rev. Lett. **97**, 093202 (2006).

[15] M. Schulz, M. Durr, B. Najjari, R. Moshammer, and J. Ullrich, Phys. Rev. A **76**, 032712 (2007).

[16] Note that (the first draft of) the present paper is available; see A. Voitkiv and B. Najjari, e-print arXiv:0810.4926.

[17] F. Martin and A. Salin, Phys. Rev. A **55**, 2004 (1997).

[18] D. S. F. Crothers and J. McCann, J. Phys. B **16**, 3229 (1983).

[19] A. B. Voitkiv, B. Najjari, and J. Ullrich, J. Phys. B **36**, 2325 (2003).