# Three-body quantum dynamics of helium single ionization by 1 GeV/u $U^{92+}$ impact

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**Abstract**

We study the fully differential cross section for single ionization of helium by 1 GeV/u $U^{92+}$ impact with emission of low-energy electrons ($\sim 2-10$ eV) in collisions with 'intermediate' momentum transfers ($\sim 0.5-1$ a.u.). These collisions belong to a new collision regime (for which the basic dynamics of ion-atom collisions have never been explored before) where the impact velocity approaches the speed of light and the minimum momentum transfer is very small, but the ratio of the projectile charge to the collision velocity is of order of unity. It is shown that higher order terms in the interaction between the projectile and the active target electron do not affect the ionization dynamics. In contrast, the interaction between the projectile and the target core has a profound impact on the shape of the fully differential cross section changing the binary-to-recoil-peak ratio by 2-3 times.

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Collisions of fast highly charged ions with helium represent very interesting examples of quantum dynamical few-body systems [1]. The basic dynamics of such collisions is explored by considering the fully differential cross section (FDCS). The parameter $\eta_p = Z_p/v_p$, where $Z_p$ is the projectile charge and $v_p$ the collision velocity, is commonly used to characterize the effective strength of the projectile-target interaction. At small values of $\eta_p$ ($\eta_p \ll 1$) the experimental FDCS was very well reproduced for electrons emitted into the scattering plane, which is spanned by the vectors of the initial and final projectile momenta. However, for electrons emitted outside the scattering plane, serious discrepancies were found even to state-of-the-art calculations [2]. The difficulties with understanding the basic collision dynamics become even more severe with increasing $\eta_p$ [3]- [4]. For collisions with 3.6 MeV/u $Au^{53+}$ projectiles, where $\eta_p$ is large ($\eta_p = 4.4$), dramatic deviations between experiment and theory were found both inside and outside the scattering plane [5].

The poor description of the data out of the scattering plane at small $\eta_p$ by theory was attributed to an incomplete treatment of the projectile - target-core interaction [2] (below referred to as the *n*-*n* interaction), which later was also identified as one factor leading to the poor agreement at large $\eta_p$ [4]. Therefore, it became evident that a thorough understanding of the basic collision dynamics in single ionization necessitates detailed studies of the role of the *n*-*n* interaction. Since the role of this interaction increases with $\eta_p$, it is desirable to perform such studies at relatively large $\eta_p$ (e.g. $\eta_p \sim 1$). However, with increasing $\eta_p$ the role of higher-order terms in the interaction between the projectile and the active target electron also becomes more important and for collision systems studied so far it was practically impossible to disentangle these two factors influencing the FDCS. Indeed, can one find a collision regime, where the higher-order terms in the interaction between the projectile and the active electron are negligible but the *n*-*n* interaction is very important, which would be very suitable to study systematically the role of the latter ?

In this Letter, by exploring the dynamics of helium single ionization by 1 GeV/u $U^{92+}$ projectiles in collisions with 'intermediate' momentum transfers $q \sim 0.5$ - 1 a.u., we demonstrate that such a collision regime does exist. The collision energy corresponds to a projectile speed of $v_p = 120$ a.u. which is 88% of the speed of light $c = 137$ a.u.. At the same time $\eta_p = 0.77$ and thus is rather close to unity. The minimum momentum transferred to the target in the collision is given by $q_{min} = (\varepsilon_k - \varepsilon_0)/v_p$, where $\varepsilon_0$ and $\varepsilon_k$ are the energies of the initial and final target states, respectively. In our case, due to the very large impact velocity, this momentum does not noticeably exceed $\sim 10^{-2}$ a.u.. This means that we enter a qualitatively new collision regime, which so far has not been studied on the level of the FDCS, where relatively large values of the 'perturbative strength' $Z_p/v_p$ are combined with very small minimum momentum transfers. It will be seen below that in the collision regime under consideration there exist very pronounced effects of the *n*-*n* interaction on the FDCS but, in spite of the relatively large value of $\eta_p$, higher-order terms in the projectile - active target electron interaction are unimportant.

**Experiment**. A fully differential experiment on single ionization requires measuring the momentum vectors of two of the three collision fragments, the momentum vector of the third fragment is then readily determined by momentum conservation. In this work we measured the momentum vectors of the ionized electron and the recoiling target ion.

The experiment was performed at the GSI (Darmstadt, Germany). A $U^{92+}$ beam was collimated to a size of about 1 mm. Next, the projectile ions were guided to the interaction region where the ion beam intersected a neutral He beam from a supersonic gas jet. A switching magnet was used to analyze the projectile charge state after the collision and the projectiles which did not change charge state were detected by a scintillator.

The energy transferred during the collision from the projectile to the recoil ion is typically of the order of thermal energy at room temperature. Therefore the target beam was cooled to a temperature of less than 1 K using a three-stage supersonic gas jet. A nearly uniform electric field of about 5 V/cm in the collision region was used to extract the recoil ions parallel and the ionized electrons anti-parallel to the incident beam. After the electric field region, the recoil ions and the electrons travelled through a field free region and were detected by two-dimensional position-sensitive detectors. A uniform magnetic field of 17 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. Both the recoil ions and the electrons were measured in coincidence with the projectiles which did not change charge state. The transverse momenta of the recoil ions and the electrons were obtained from the position information of the detectors. The longitudinal momentum component was determined from the time of flight of each particle from the collision region to the respective detector obtained from the coincidence times. The momentum vector of the scattered projectile was deduced from momentum conservation.

**Theory.** In order to consider theoretically helium single ionization in relativistic collisions with highly charged ions we have developed a new approach. A detailed description of this approach as well as its correspondence with the first order perturbation theory will be given in a separate publication. Here we just briefly discuss the key points of this approach.

Firstly, helium single ionization is regarded as a three-body problem (projectile, 'active' electron, target core). Taking into account that the majority of electrons emitted from such a light target like helium has velocities with respect to the recoil ion not exceeding a few atomic units, the process is considered in the target rest frame and the active electron and the target core, which consists of the target nucleus and the 'passive' electron, are described nonrelativistically. Secondly, the projectile-target coupling is treated within the symmetric eikonal approximation (SEA) [1], where the relativistic interactions

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[1] Note that the non-relativistic SEA was used for calculating electron excitation in ion-atom collisions (see e.g. [6]). The relativistic version of the SEA, in which the electron is described by the Dirac equation, also exists but was shown to lead to unphysically large spin-flip contributions in the limit of low collision velocities. This shortcoming is absent in the 'semi-relativistic' version of the SEA, which is used here and where the motion of the target subsystem is described by the Schrödinger-Pauli equation and the

of the projectile with the active target electron and the target core are explicitly taken into account. Both in initial and final channels the projectile velocity is almost by two orders of magnitude higher than typical electron velocities ($\sim$ 1-2 a.u.). Therefore, the SEA, in which the distortion of the target states due to the projectile field is accounted for by (asymptotic) eikonal factors, is expected to be a very good approximation. In the treatment of the *n*-*n* interaction the target core is regarded as a point-like charged object which couples to the field of the relativistic projectile via an effective charge $Z_{t,eff}$. This charge is a free parameter of the theory and in general can be considered as dependent on the total momentum transfer $q$ in the collision. Following [7]- [9] in our calculations reported below we set $Z_{t,eff} = 1$. Thirdly, the initial and final states of the 'active' electron in the unperturbed target are treated in a Hartree-Fock approximation. We shall call the model briefly described in this paragraph the SEA-HF model.

The first-order counterpart of the effective three-body model for helium single ionization, discussed above, is obtained if the same Hatree-Fock description of the active electron is used as in the SEA-HF model but the projectile-target interaction is dealt with in the first Born approximation (FBA). Below this model will be referred to as the FBA-HF model. In the FBA the *n*-*n* interaction does not contribute to the transition amplitude and the interaction between the projectile and the active target electron is reduced to just a single-photon exchange.

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 $\mathbf{q} = (\mathbf{Q}, q_{min})$ and $\mathbf{k}$ is the momentum of the emitted electron with respect to the target nucleus. We shall restrict our discussion to the electron emission into the collision plane.

In figures 1-4 we plot the FDCS in collisions with 1 GeV/u $U^{92+}$ projectiles as a function of the polar angle, $\vartheta_{\mathbf{k}} = \arccos(\mathbf{k} \cdot \mathbf{v}_p / k v_p)$, of the emitted electron. Theoretical results shown in these figures are on an absolute scale (in a.u.). The experimental data are normalized to results of the most advanced theoretical model (the SEA-HF model with including the *n*-*n* interaction) at the cross section maxima. Both the experimental and theoretical results show that the emission pattern consists of the so called binary and recoil peaks which are centered approximately at $90^0$ and $270^0$, respectively.

Two important conclusions can be drawn from these figures. Firstly, despite the ratio $Z_p/v_p$ is rather close to 1, results of the FBA-HF calculations turn out to be very similar to results of the eikonal calculation if in the latter the *n*-*n* interaction is ignored. Thus, for the relatively large momentum transfers under consideration, higher-order effects in the interaction between the projectile and the active target electron are of minor importance. This situation can be contrasted with the case of helium ionization by 2 MeV/u $C^{6+}$ impact with the same total momentum transfers studied in [7]- [9]. For the latter collisions (illustrated by an example shown in figure 5) we have performed calculations within a three-body collision model in which the Continuum-Distorted-Wave-Eikonal-Initial-State

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projectile is treated relativistically.

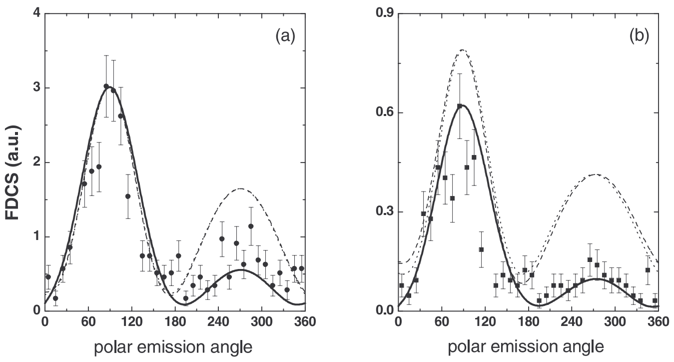

Figure 1: The FDCS for single ionization of helium by 1 GeV/u $U^{92+}$ projectiles plotted as a function of the polar emission angle. The electron emission energy $\varepsilon_k = 2$ eV and the total momentum transfer (a) $q = 0.65$ a.u. and (b) $q = 1$ a.u.. Symbols: experimental data, these data have been fit to the maximum of the thick solid curve. Thick solid curve: results of the SEA-HF model, the *n*-*n* interaction is included. Dash curve: results of the SEA-HF model, the *n*-*n* interaction is ignored. Dot curve: results of the FBA-HF model.

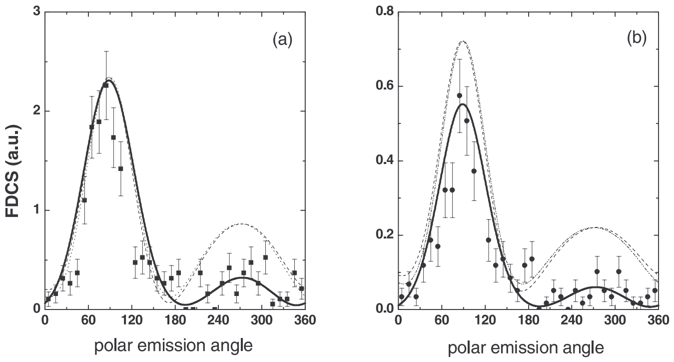

Figure 2: Same as in figure 1 but for $\varepsilon_k = 4$ eV. (a) $q = 0.65$ a.u. and (b) $q = 1$ a.u..

(CDW-EIS) approximation (with and without the inclusion of the *n*-*n* interaction) is combined with the same HF description of the active electron as in the SEA-HF [2]. It is clearly seen in figure 5 that there is a very noticeable difference between results of the FBA and the CDW-EIS without including the *n*-*n* interaction which means the existence of a considerable contribution from the higher order terms in the projectile-active-electron interaction. Since for 2 MeV/u $C^{6+}$ and 1 GeV/u $U^{92+}$ projectiles the ratio $Z_p/v_p$ is quite close, the different roles played by the higher order terms in this interaction should be attributed to the very large differences in the collision velocities and the corresponding minimum momentum transfer.

Secondly, according to our calculation the role of the *n*-*n* interaction is very substan-

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[2] Note that if collision velocities are high enough (but relativistic effects are still not important) the CDW-EIS-HF and SEA-HF models yield practically identical results.

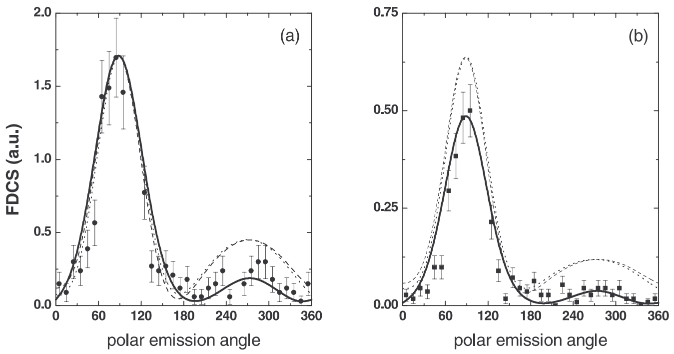

Figure 3: Same as in figure 1 but for $\varepsilon_k = 7$ eV. (a) $q = 0.65$ a.u. and (b) $q = 1$ a.u..

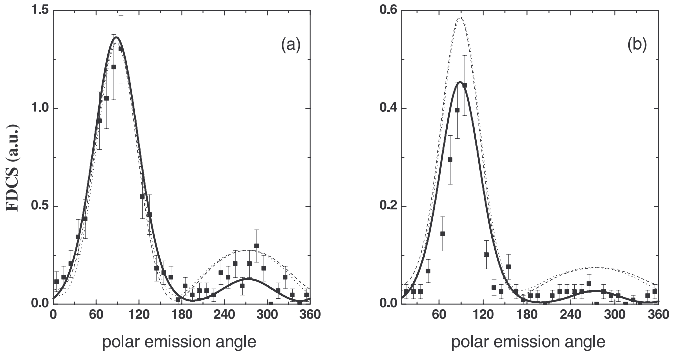

Figure 4: Same as in figure 1 but for $\varepsilon_k = 10$ eV. (a) $q = 0.65$ a.u. and (b) $q = 1$ a.u..

tial. For the collision parameters under consideration, this interaction practically does not influence the binary peak for collisions with $q = 0.65$ a.u. and not very substantially affects this peak for $q = 1$ a.u.. However, the $n$-$n$ interaction has a strong impact on the recoil peak and, thus, on the shape of the cross section. Indeed, this interaction reduces the recoil-to-binary-peak ratio by a factor of 2-3 compared to the predictions of the FBA and brings the calculated ratio and the shape of the cross section in much better overall agreement with the experiment.

In summary, we have presented experimental and theoretical results for the FDCS for helium single ionization by 1 GeV/u $U^{92+}$ projectiles. This is the first time when the FDCS is explored for collision velocities approaching the speed of light where the minimum momentum transfer to the target becomes very small and close to that typical for helium single ionization via the photo effect. Despite the high velocity, the ratio $Z_p/v_p$ is rather close to unity and the transverse momentum transfers are of order of 1 a.u. effectively corresponding to relatively small impact parameters ( $\sim$ 1 a.u.) that enables to expect substantial deviations from predictions of the FBA.

The interaction between the projectile and the target core, which itself does not lead

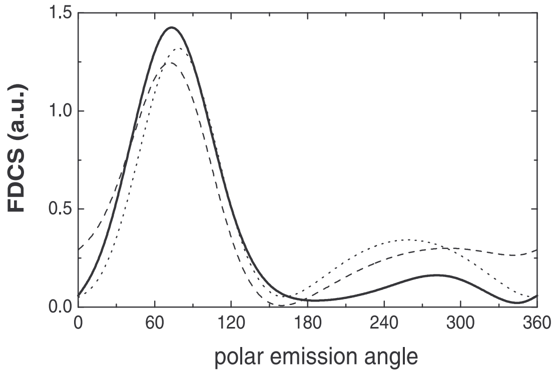

Figure 5: The FDCS for single ionization of helium by 2 MeV/u $C^{6+}$ projectiles. $q = 0.65$ a.u. and $\varepsilon_k = 7$ eV. Thick solid curve: results of the CDW-EIS-HF model, the *n*-*n* interaction is included. Dash curve: results of the CDW-EIS-HF model, the *n*-*n* interaction is ignored. Dot curve: results of the FBA-HF model.

to ionization, has been shown to be of great importance for a proper description of the basic collision dynamics. However, the higher order terms in the interaction between the projectile and the active target electron turned out to be unimportant. This clear 'separation' of the *n*-*n* interaction, as the main mechanism not included in the FBA, is attributed to the very large impact velocity.

As last remark, in our case the collision Lorentz factor, $\gamma = (1 - v_p^2/c^2)^{-1/2}$, is equal to 2.07 and, hence, considerable relativistic effects in the ionization dynamics can in general be expected. However, according to both the FBA and SEA, single ionization of helium accompanied by the emission of low-energy electrons is very substantially influenced by relativistic effects only in collisions with relatively small momentum transfers (close to $q_{min}$) which are presently not accessible to experimental observations. For momentum transfers considered here ($\sim 0.5 - 1$ a.u.) these effects are very weak [3].

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[3] Although the probability of electron spin-flip transitions increases with increasing $q$, for $q \sim 1$ a.u. the ionization cross section with spin-flip is still suppressed by a factor $v_p^2/c^4$ compared to that without spin-flip.

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