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Comment on "Singly Ionizing 100-MeV/amu C^{6+}+He Collisions with Small Momentum Transfer"

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In a recent article, Kouzakov *et al.* [Phys. Rev. A **86**, 032710 (2012)] suggested that experimental resolution effects can be responsible for discrepancies between measured and calculated fully differential cross sections for the ionization of helium by fast C^{6+} impact. They further asserted that projectile-coherence effects have no influence on the measured cross sections. In this Comment, we reiterate that the experimental resolution can only explain part of the discrepancies. Furthermore, we note that the conclusion regarding the role of projectile coherence neglects potential interference between first- and higher-order transition amplitudes.

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In a recent article, Kouzakov *et al.* [1] presented a theoretical study on the single ionization of He by 100 MeV/amu C^{6+} impact, based on the first Born approximation (FBA), the second Born approximation, and on the distorted-wave Born approximation. They asserted "that experimental uncertainties, including those due to a velocity spread of the He gas atoms in a supersonic jet, can be responsible for the observed disagreement." In this Comment, we emphasize that the resolution can only explain part of the discrepancies found between experiment and numerous calculations [e.g., Refs. [2–6]]. To associate the disagreement entirely with the resolution would imply values which can be ruled out by the measurement.

The discrepancies between experiment and theory occur mainly in the fully differential cross section (FDCS) for electron ejection into the plane spanned by the initial projectile momentum $\mathbf{p}_o$ and the axis perpendicular to the momentum transfer $\mathbf{q}$ to which we refer in the following as the perpendicular plane. There, pronounced peak structures were observed in the measured FDCS, whereas, theory predicts a nearly isotropic angular dependence. In order to investigate whether the experimental resolution can lead to peak structures, Kouzakov *et al.* convoluted their FBA calculation with the experimental resolution in $\mathbf{q}$. When they use the reported experimental values ($\Delta q_x = 0.23$ a.u. in the direction perpendicular to the target jet and $\Delta q_y = 0.46$ a.u. in the jet direction), indeed, a peak structure is found in accordance with our analysis of the influence of the resolution [7,8]. However, the magnitude of the FDCS is nearly an order of magnitude smaller than in experiment. In order to reproduce the magnitude, Kouzakov *et al.* had to use a resolution of at least $\Delta q_x = 0.65$ and $\Delta q_y = 1.3$ a.u. However, the resulting improved agreement with the data does not justify their conclusion "that experimental uncertainties, including those due to a velocity spread of the He gas atoms in a supersonic jet, can be responsible for the observed disagreement." The values for the thermal momentum spread in the target beam, that they assumed were inconsistent with the experimental single differential cross sections in q_x and q_y, we reported in Ref. [8]. The q_x and q_y—dependence of these data has a full width at half maximum of 0.6 and 0.8 a.u., respectively. Since this width is a combination of the width due to true physics effects and the resolution, it provides an upper limit for the latter, as detailed in Ref. [8]. The observed peak structure can only partly (less than 50%) be attributed to the experimental resolution.

In Ref. [8], we found that convoluting the FBA with classical elastic scattering between the heavy particles in the collision leads to much improved agreement with the experimental data. Kouzakov *et al.* asserted that this approach is questionable because it treats the two collisions incoherently. We note that coherence considerations enter primarily in the treatment of the transition amplitudes contributing to the FDCS. The most important higher-order amplitudes for this collision system are those containing the nucleus-nucleus (NN) interaction. This amplitude is likely to mostly contribute at significantly different impact parameters than the first-order amplitude [9]. Observable interference between these amplitudes can only occur if the projectile beam is coherent [10]. However, in the experiment, the transverse coherence length Δr was 3 orders of magnitude smaller than the atomic target size, and the projectile beam was, thus, likely incoherent. Like all fully quantum-mechanical models not based on time-dependent wave-packet propagation, those of Kouzakov *et al.* also effectively assume $\Delta r = \infty$, whereas, the convolution of the FBA with classical elastic scattering uses classical trajectories (corresponding to $\Delta r = 0$) as far as the NN interactions are concerned. Neither assumption reflects the very small but nonzero experimental Δr exactly, but the latter seems to represent a more realistic approximation of the actual coherence length. Therefore, although we agree with Kouzakov *et al.* that the approach of Ref. [8] is formally not as rigorous as a fully quantum-mechanical approach, for such an extremely small Δr, it is not clear that a fully coherent treatment is more adequate than a fully incoherent treatment. Despite its limitations, the method of Ref. [8] provides qualitative clues regarding the role of the projectile coherence.

Kouzakov *et al.* question that projectile coherence can affect the FDCS for atomic targets because there is no two-center target potential involved. This argument neglects the possibility of interference (for coherent beams) between first- and higher-order amplitudes as described above for which a two-center target potential (in analogy to optical single-slit interference) is not required. Indeed, such interference has been reported in a recent theoretical study [11]. On the other hand, this type of interference is obviously not accounted for in the FBA. It is, thus, not surprising that a convolution of the FBA with the initial projectile wave packet does not change the FDCS. A proper theoretical test of the potential influence of the projectile coherence should be performed with a higher-order model. Experimentally, the important role of the projectile coherence in the FDCS for the ionization of atomic targets was recently confirmed [12]. However, this does not necessarily imply that the discrepancies between experiment and theory (after accounting for the resolution) are exclusively due to coherence effects.

It should be noted that, in fully differential measurements on ionization by electron impact, the projectile beam is usually coherent because of the much larger de Broglie wavelength compared to ion impact. Indeed, such data can now be well described (at least qualitatively) by nonperturbative models assuming a coherent beam [13].

As a final note, we join Kouzakov *et al.* in encouraging independent experiments cross-checking our results reported in Ref. [2]. Moreover, further experimental work is called for to provide evidence for (or disproof of) our interpretation that part of the discrepancies can be associated with the projectile coherence properties. The results of Ref. [12] provide strong support, but there, the data for the coherent and incoherent beams were not taken in the same experiment and for different ion species. Due to the extremely small de Broglie wavelength of a 100 MeV/amu C^{6+} projectile, it is practically impossible to prepare a coherent beam for this ion species even using electron cooling as was performed in Ref. [12]. Therefore, experiments should be carried out for coherent and incoherent proton beams, varying Δr by changing the distance of the collimating slit to the target, under otherwise identical conditions as was performed by Egodapitiya *et al.* [10].

To summarize, although we agree that the experimental resolution has to be carefully analyzed (which we did in Refs. [7,8]) and that it can lead to structures in the perpendicular plane, it is not the main contributor to the discrepancies between experiment and theory. Recent experimental studies suggest that the role of the projectile coherence on the presence or absence of interference between various transition amplitudes has to be carefully considered [10,12]. From first principles, this cannot be performed using the FBA.

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