Reply to "Comment on 'Appearance and disappearance of the second Born effects in the $(e,3e)$ reaction on He' "

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In this Reply, we demonstrate that at large momentum transfer ($|q|=2$ a.u.), within the experimentally accessible angular range of the ionized electrons, there is good agreement between experiment and the first Born calculation concerning the shape of the cross section. Furthermore, we show that the fact that our results for $(e,3e)$ double ionization seemingly "contradict well-accepted results in $(e,2e)$ single ionization" can be traced to a second Born process in which the projectile interacts with both target electrons in sequence. This process competes effectively with other double ionization mechanisms but is relatively unimportant for single ionization.

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In a recent publication [1], we analyzed the symmetry of the $(e,3e)$ cross section observed for $(e,3e)$ two kinematical situations: a small momentum transfer $|q|=0.8$ a.u. and a large momentum transfer $|q|=2.0$ a.u. From this analysis, we drew conclusions concerning the order of the projectile target interaction. A first-order process must show reflection symmetry of the cross section with respect to the momentum transfer direction $\boldsymbol{q}$ (in the following abbreviated by q symmetry) while a second-order collision may violate this condition. We stated that while for small momentum transfer the q symmetry is strongly violated, for large momentum transfer the experimental cross section does not contradict a q symmetry and is in good agreement with the first Born calculation presented. We concluded that higher-order processes are absent for large momentum transfer collisions.

In their Comment, Lahmam-Bennani *et al.* analyze the q symmetry of the experimental cross section. For this purpose, Lahmam-Bannani *et al.* reflect peak B at the line S obtaining position B'' (Fig. 1 and Fig. 2 in their Comment). This reflection is useful to magnify deviations from the perfect q symmetry since a shift of peak B (or B', respectively) along the dashed line will give rise to the same shift of point B'' in the opposite direction, resulting in this shift multiplied by 2 in the distance of peaks B' and B''. The result of this analysis is reliable if the position of the cross-section peaks under question can be determined unambiguously, as is the case for low momentum transfer $|q|=0.8$ a.u., where Lahmam-Bennani *et al.* agree with our analysis. On the other hand, it fails if the true position cannot be determined, as is the case at large momentum transfer. The cross-section peak B in Fig. 1 of the Comment by Lahmam-Bennani *et al.* is positioned right at the edge of the experimentally accessible angular range marked by circular lines in the diagram. Therefore, the maximum of the visible part of peak B is not necessarily identical with the true position of the cross-section maximum. Thus in the original paper [1], we do not claim, as is asserted by Lahmam-Bennani *et al.*, that the cross section shows complete q symmetry, but we do state that it is indeed consistent with this symmetry.

In order to demonstrate the agreement with the first Born calculation, in Fig. 1 we present three particular cuts through the cross sections for $q=2$ a.u. which allow a more quantitative discussion as compared to the two-dimensional density plots given in our original paper. For a fixed emission angle θ_c of the one ejected electron, the angle θ_b of the second electron is scanned. We have chosen angles $\theta_c=-36^{\circ}$, 12°, and 48° in order to cover a large part of the cross section obtained experimentally. Since in the experiment no absolute cross sections are measured, all experimental data are multiplied by one common factor to fit the overall magnitude of the theoretical results. It is clearly seen that while the full angular range of θ_b is not seen experimentally, for the chosen angles θ_c, the experiment covers all angles θ_b where calculation predicts the highest cross sections. Without reference to any theory, it is generally accepted that for equal energies, the cross section vanishes for small relative angles of the ejected electrons, i.e., $\theta_b=\theta_c$, due to the Coulomb repulsion of the electrons. This feature is clearly reproduced by the calculation which treats the fragmenting He atom, a three-body Coulomb system, with full correlation. For increasing relative emission angles, the cross section rises showing the two-peak structure which we discussed in our original paper (peaks A and B). Theory reproduces this structure nicely concerning the angular positions. The relative magnitude of the peaks is reproduced within the experimental statistics in Figs. 1(b) and 1(c), while in Fig. 1(a) there is a discrepancy of the magnitude of peak B which is statistically significant. Compared to the low momentum transfer case where, as is confirmed by the authors of the Comment, the first Born result fails completely to describe the experimental data, here the first Born calculation is in good agreement. Of course, we have to stress that this conclusion is valid only within the angular range discussed, which, from present experimental restrictions, does not cover the full solid angle. In particular it is not possible to examine angular combinations (θ_b,θ_c) in the range of (250°,90°) or (90°,250°), respectively. The lack of corresponding experimental data is the origin of the violation of the q symmetry of the density representations of

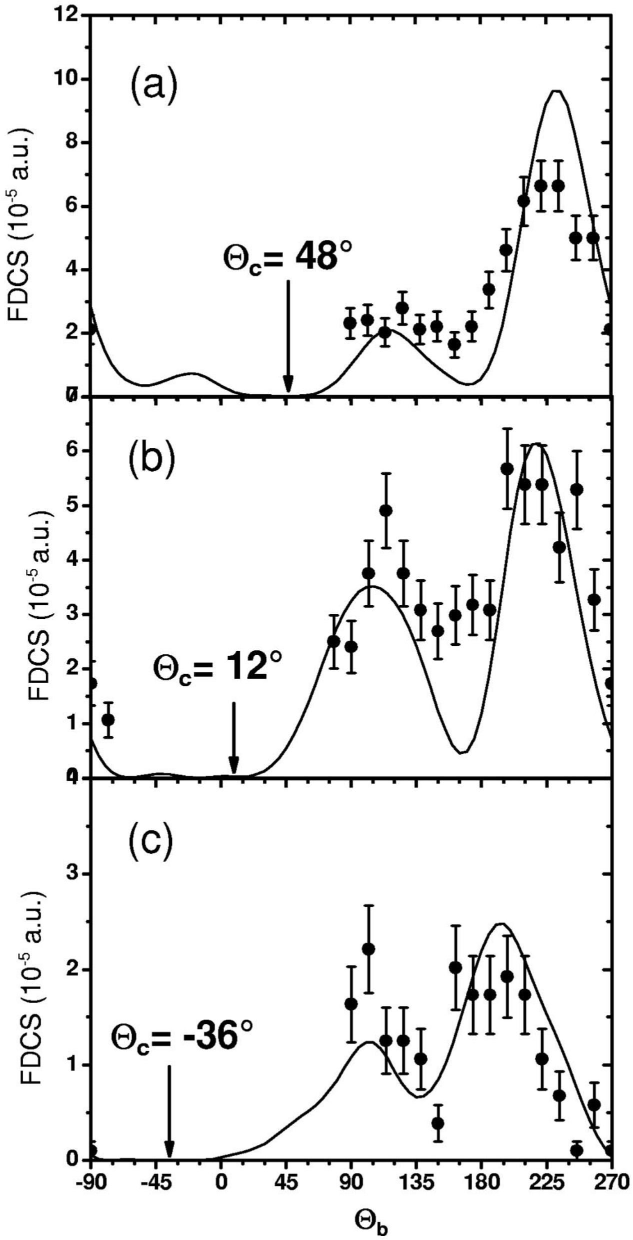

FIG. 1. Fivefold differential cross section (FDCS) for E_0 =500 eV in coplanar scattering geometry for equal energy sharing of the two ionized electrons ($E_{b,c}$=5 eV). The momentum transfer by the scattered projectile is $|q|=2.0\pm0.3$ a.u. The emission angles $\theta_{b,c}$ of the ejected electrons are measured with respect to the projectile beam forward direction. The angle θ_c of one electron is fixed as indicated in the diagrams: θ_c=48° (a), θ_c=12° (b), and θ_c =−36° (c). The angle θ_b of the second electron is scanned. Continuous lines: first Born convergent close-coupling calculation (CCC).

Fig. 2 in [1]. The authors of the Comment argue that comparison of the peak positions with first-order theory is not a proper method to judge the q symmetry. Nevertheless, we claim that the agreement of the experimental data in shape with a first-order theory implies that the q symmetry is fulfilled in the angular range examined, since this is the case for the theory by definition.

Therefore, we have to reject the statement of Lahmam-Bennani *et al.* in their Comment that our data do not allow any conclusions concerning the agreement with a first-order process. Within the accessible angular range, it does allow these conclusions. We admit that the data presented in [1] do not allow to exclude second-order collisions to contribute for angular combinations outside the range discussed or for the remaining, compared to the $|q|=0.8$ a.u. case, minor discrepancies from the first-order model within the angular range discussed.

In the second paragraph, the authors of the Comment refer to an analysis of the $(e,2e)$ single ionization of He in the planar asymmetric kinematics (a so-called Ehrhardt geometry). They cite the work by Ehrhardt *et al.* [2], who indicated deviations between the first and second Born calculations which grew larger as the momentum transfer was increasing. We have to challenge this interpretation. The calculations presented by Ehrhardt *et al.* [2] were based on the plane-wave description of the projectile. Subsequent work by Franz and Altick [3] showed that an equally good description of the Ehrhardt-type experiments [4] at a reasonably high impact energy (400–600 eV) can be achieved within the first Born model simply by improving the quality of the final-state wave function. In some cases this improvement can be achieved merely by switching from a plane-wave description of the projectile to the distorted waves, as illustrated in Fig. 2. Here a substantial improvement of the calculated triple differential cross section, especially a greatly reduced binary-to-recoil ratio, is achieved by including the distorted potential of the target on the projectile before and after collision. We stress that both the distorted waves (DWBA) and the plane waves (PWBA) calculations are performed within the first Born approximation as far as the interaction of the projectile with the target electron is concerned. It is upon this interaction that we place our classification of the first and second Born processes.

The authors of the Comment claim that the nuclear term corresponding to the interaction of the projectile with the residual ion plays somehow a greater role in the second-order calculations, while it is vanishing in the first Born approximation due to the orthogonality of the target initial and final wave functions. Here they confuse the physics with technicalities. The nucleus term is equally important/unimportant in the first and second Born calculations. Had the authors of Ref. [2] evaluated the second Born term exactly on the proper target state wave functions, the nuclear term would have disappeared as it had in the first Born term. The nonorthogonality problem arises because of the closure approximation. On the other hand, both the first and the second Born amplitudes in the original paper of Dorn *et al.* [1] were evalulated with nonorthogonal ground- and final-state wave functions and the nuclear term was present in both amplitudes.

The real difference between the $(e,2e)$ and $(e,3e)$ processes is not in the role of the projectile interaction with the nucleus. It is in the nature of the double ionizing collision, which is a weak process strongly driven by the electron correlation. On the contrary, the single ionization is a strong process which is only marginally modified by the electron correlation.

Correspondingly, the role of the second Born processes is

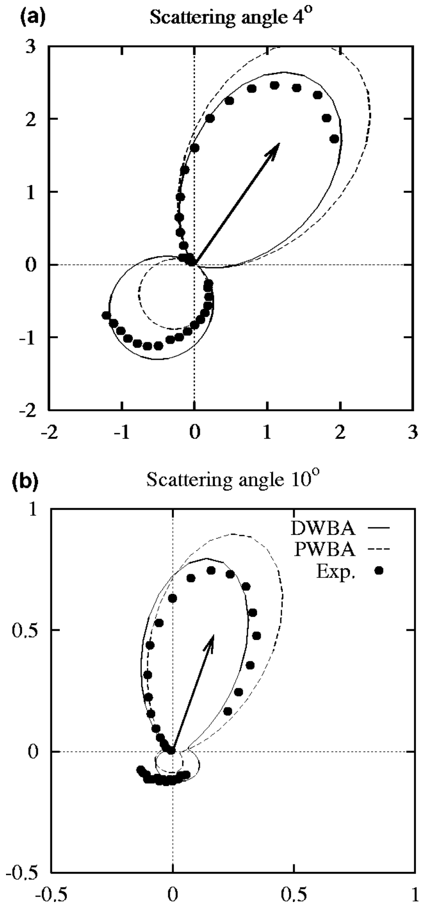

FIG. 2. Triple differential cross section of the $(e,2e)$ on He at $E_0 = 400$ eV and $E_b = 10$ eV in the coplanar geometry. The scattering angle θ_a and the momentum transfer $|q|$ are 4° and 0.44 a.u. (left panel) and 10° and 0.95 a.u. (right panel). The momentum transfer direction is indicated by an arrow. The first Born calculation with the distorted waves (DWBA) and the plane waves (PWBA) is indicated by the solid and dashed lines, respectively. The absolute experimental data are from [4].

different in the $(e,2e)$ and $(e,3e)$ reactions. In $(e,3e)$, the second Born process is an essential mechanism of removing the second target electron. It cannot be incorporated, or accounted for, by modifying the final continuum state, as seems to be the case in the $(e,2e)$ reaction at a comparable impact energy.

Recently, van Boeyen *et al.* [5] have given very illustrative reasons why for impulsive $(e,3e)$ collisions no second Born contributions are observed in the projectile scattering plane. They analyzed in detail the collision kinematics for a case where the ejected electrons carry the projectile momentum transfer (the Bethe ridge kinematics) and concluded that the electrons ionized by a second Born process should appear outside the projectile scattering plane. They clearly confirmed this analysis experimentally for 1059 eV electron impact on magnesium for $|q| = 3$ a.u. momentum transfer. Despite the fact that the kinematical conditions of our experiment are not identical, the results of van Boeyen *et al.* are consistent with our observation inside the scattering plane. Consequently, in order to detect second Born processes at large momentum transfer, one should investigate electron emission outside the scattering plane. The absence of second Born effects inside the scattering plane for large $|q|$ therefore might soon become well accepted despite the fact that the scientific community takes it as unexpected and surprising in the first place.

From the above discussion, it becomes clear that it would be an important step forward to have access to the full solid angle of the final-state electrons without restrictions. Therefore, experiments are presently in preparation in our group which will cover the full angular range for both ejected target electrons. This is enabled by applying a new delay-line detector with hexagonal delay-line read-out developed by the RoentDek company [6]. This detector allows detection of several simultaneously hitting electrons without dead-time restrictions. We expect the results of this experiment to unambiguously disclose the symmetry of the cross section without the present restrictions.

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