Postcollision effects in target ionization by ion impact at large momentum transfer

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(Received 18 June 2013; published 9 August 2013)

We have measured and calculated fully differential cross sections for target ionization in 16-MeV O^{7+} + He and 24-MeV O^{8+} + Li collisions. As in previous studies, in the case of the He target we observe a pronounced forward shift in the angular distribution of the electrons relative to the direction of the momentum transfer $\mathbf{q}$ at small q ($q < 1$ a.u.). An unexpected result is that we also find a strong forward shift at large q ($q > 2$ a.u.), while at intermediate q this shift becomes very weak or even turns into a backward shift. For the Li target, in contrast, the forward shift monotonically increases with increasing q. These observations are qualitatively reproduced by our calculations. The comparison to theory suggests that at large q the forward shift is due to the postcollision interaction between the outgoing projectile and the ejected electron, but at small q it is mostly due to an interplay between the projectile-target core interaction and the electron-target core interaction.

DOI: 10.1103/PhysRevA.88.022704 PACS number(s): 34.50.Fa

I. INTRODUCTION

In the case of electron impact kinematically complete experiments on target ionization have routinely been performed for decades (see, e.g., [1–6]) since the pioneering work of Ehrhardt *et al.* [7]. The fully differential cross sections (FDCSs) extracted from such measurements offer the most sensitive tests of theoretical models and the results revealed the formidable challenge theory was facing. It took several decades before a satisfactory (although not perfect) comprehensive understanding of the ionization dynamics emerged at least for the two simplest target atoms H and He [6].

Kinematically complete experiments on ionization by ion impact are much more challenging because the projectile scattering angles θ_p are typically more than three orders of magnitude smaller than for electron impact because of the much larger mass. Multiple differential data measuring θ_p directly so far have been obtained only for light ions at low to intermediate energies [8–10]. For heavy and/or fast ions kinematically complete experiments became feasible only with the development of cold target recoil-ion momentum spectroscopy [11] and reaction microscopes [12], where the complete momentum vectors of the recoil ions and the ejected electrons are measured. The projectile momentum, more specifically the momentum transfer $\mathbf{q}$ from the projectile to the target atom (and thereby θ_p), is then determined from momentum conservation.

Initially, it was not clear to what extent data extracted from kinematically complete experiments for ion impact could provide new physics insight relative to what was known already from electron-impact studies. At slow projectile velocities, one could have expected such new insight because of the qualitatively different nature of the two-center potential generated by the projectile and the target nucleus: In contrast to electron impact, this potential supports the formation of molecular states in the case of ionic projectiles. Indeed, in nearly fully differential data (one of the electron-momentum components was not determined) rich structures were observed that can be understood within a quasimolecular model [13]. However, such molecular effects are insignificant at large projectile energies and FDCSs measured for electrons ejected into the scattering plane in fast C^{6+} + He collisions [14] looked practically identical to those measured for electron impact at a similar perturbation parameter η (projectile charge to speed ratio) (see, e.g., [15]).

Another interesting kinematic regime is represented by collisions that are too fast for molecular effects to be significant, but for which η is nevertheless large enough (due to a large projectile charge) for higher-order contributions to the ionization cross sections to be important. For slow electron impact it has been known for a long time that continuous interactions between the projectile and the ejected electrons after the primary interaction lifting the target electron to the continuum (i.e., higher-order contributions in the projectile-electron interaction), known as postcollision interaction (PCI), can strongly affect the shape of the angular dependence of the FDCS [1]. Since the interaction between these two particles is repulsive PCI leads to a backward shift of the electron-emission pattern compared to the pattern one would get for a first-order process. Accordingly, for ion impact the corresponding attractive PCI should lead to a forward shift. For slow projectiles PCI effects are difficult to observe because they tend to be masked by the aforementioned molecular effects. However, for fast highly charged ion impact such a forward shift was observed for various collision systems [16,17].

This high-energy–large-η regime is not accessible in electron-impact studies because the ionization threshold sets a minimum required projectile speed corresponding to a maximum η of about 0.74 for a helium target. Furthermore, at the beginning of the millennium FDCS measurements for fast highly charged projectiles still represented a completely unexplored regime. The forward shift observed later was interpreted as an attractive PCI effect [16–18], however, initially it was not clear to what extent the role of PCI for fast highly charged ion impact could be regarded as being understood. There were severe discrepancies between experiment and theory, but these seemed to be at least partly associated with the interaction between the projectile and the target core (PT interaction) and not necessarily with PCI [16–18]. Higher-order effects involving the PT interaction were found to be surprisingly important even for very small η if electron ejection outside the scattering plane was considered [19].

The out-of-plane data of Ref. [19], as well as FDCSs for large η, could not even be qualitatively reproduced by a variety of conceptually very different theoretical models ranging from the perturbative three-body distorted-wave approach [20] to nonperturbative close-coupling models [21], including a time-dependent approach, which led to somewhat better agreement with experiment [22]. It was difficult to understand where these theories could go so severely wrong because they all accounted for the PT interaction in a sophisticated manner. Therefore, the focus of the discussions on higher-order contributions to the FDCS somewhat shifted from mechanisms involving PCI to those involving the PT interaction. Only after a decade of vivid debates new experimental developments may have paved the road towards a resolution of this puzzle: In a series of measurements it was demonstrated that atomic scattering cross sections can, under certain conditions, significantly be affected by the projectile coherence properties [23–26], which in theory did not always reflect the experimental boundary conditions.

These experimental studies show the need to develop theoretical methods to realistically describe an incoherent projectile beam, which appears to be an interesting and new challenge. On the experimental side further work is needed to provide ultimate evidence that the discrepancies to theory are indeed at least partly caused by the projectile coherence. While the results obtained already are quite suggestive that this is the case, it is also important to determine whether this is the only (or at least the most significant) contribution to the discrepancies. For small η it is quite possible that it is, but for large η the discrepancies are so severe that it seems unlikely that they can be explained only by the projectile coherence properties. It is therefore important to redirect part of the experimental efforts to studying other higher-order effects such as the role of PCI.

In this article we report an experimental study of PCI in ionization of He and Li by ion impact at a large perturbation of about $\eta = 1$. More specifically, we aimed to investigate the relative importance of PCI as a function of q. At this point a clarification is in order: The term postcollision interaction, as well as its description given above, suggests a specific time ordering of interactions occurring between various particle pairs. However, it is not really possible to distinguish which interaction occurs first. For example, the projectile could undergo an interaction with the target electron, without ionizing the target, which is preceding, rather than succeeding the ejection of the electron. Therefore, if we define the time of the collision as the instant in which the electron is lifted to the continuum, then the term PCI refers to either a postcollision or a precollision interaction and this is how we will use this term for the remainder of this article. Our results confirm a strong forward shift at small q, as observed previously (see, e.g., [16,17]). Surprisingly, we find that this shift minimizes at intermediate q to strongly increase once again with further increasing q. These observations are qualitatively reproduced by our calculations. However, as detailed below, contrary to previous assumptions, comparison to theory suggests that only at large q can the forward shift be mostly associated with PCI; at small q the PT interaction together with an interaction between the ejected electron and the target core seems to be mostly responsible for the shift.

II. EXPERIMENT

The experiment was performed at the Test Storage Ring (TSR) in Heidelberg. Pulsed 16-MeV O^{7+} and 24-MeV O^{8+} beams (corresponding to $\eta = 1.1$ and 1.03, respectively) were cooled by means of electron cooling [27], reducing the beam size to a diameter of l–2 mm, depending on the location in the TSR. The experiment using the 16-MeV O^{7+} beam was performed with a very cold He target beam with a width of about 1 mm, which was generated by a supersonic jet. In the direction of the He beam propagation a temperature of less than 2 K was reached by adiabatic expansion. In the plane perpendicular to the expansion the beam was collimated to a transverse temperature of less than 0.2 K.

In the experiment using the 24-MeV O^{8+} beam a magneto-optical trap (MOT), which was described in detail in [28], provided a Li target cloud with a diameter of about 2 mm and a temperature of 1 mK. The momentum vectors of the electrons ejected in the collision and of the recoiling target ions were measured with a reaction microscope. Both particles were guided onto two-dimensional position-sensitive channel-plate detectors by an electric field of about 5.5 V/cm (He target) and 0.6 V/cm (Li target), respectively, in a direction nearly parallel (electrons) or antiparallel (recoil ions) to the projectile beam axis. A uniform magnetic field of 11 G (He target) or 7.7 G (Li target) forced electrons with a transverse momentum of less than 1.8 a.u. (He target) or 1.3 a.u. (Li target) into cyclotron motion with a radius small enough to hit the detector.

Both detectors were set in coincidence with a fast signal from the projectile beam buncher serving as a time reference. From the position information on each detector the two momentum components perpendicular to the extraction field of the electrons and recoil ions could be determined. The third component was obtained from a time-of-flight measurement of each particle from the collision region to the respective detector. The momentum transfer was then already determined by momentum conservation. The overall momentum resolution for the He^+ (Li^+) ions was about 0.2 a.u. (0.06 a.u.) full width at half maximum (FWHM) in the longitudinal direction and 0.35 a.u. (0.1 a.u.) FWHM in the transverse direction. For the electrons the corresponding values are 0.02 and 0.1 a.u. for both targets.

Because of the incompatibility of the magnetic fields of the MOT and the reaction microscope, the inhomogeneous MOT field was periodically switched off for 1.3 ms. In this period the cooling lasers were turned off for 200 μs, which

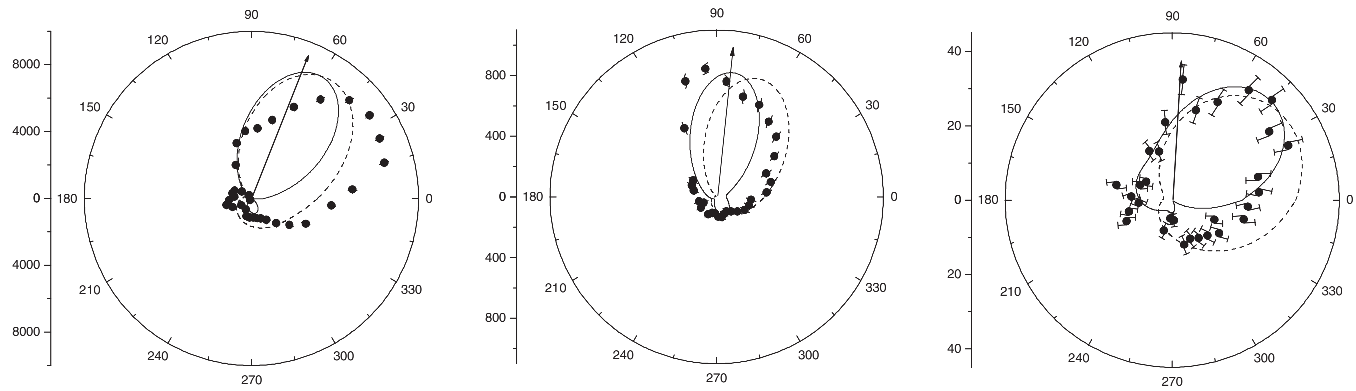

FIG. 1. Fully differential cross sections for target ionization in 16-MeV O^{7+} + He collisions for electrons with an energy of 8 ± 2 eV ejected into the scattering plane. The momentum transfer is fixed at 0.5 ± 0.1 a.u. (left panel), 1.5 ± 0.2 a.u. (middle panel), and 4 ± 0.5 a.u. (right panel). The dashed curve shows the CDW-EIS calculation and the solid curve the CDW-EIS-PT calculation.

was short enough to avoid significant expansion of the Li cloud in the MOT. Since the lifetime of the excited state is only a few nanoseconds ionization could only take place from the ground state with the valence electron in the $2s$ state during this laser-off period. In contrast, when only the MOT field, but not the cooling lasers, was switched off, the target was photoexcited to a $1s^2 2p$ configuration with a probability of about 20%. During this laser-on period data were recorded for ionization from both the $2s$ and the $2p$ state. In order to select $2s$ ionization, only data that fell within the laser-off period were analyzed.

III. RESULTS AND DISCUSSION

From the data we extracted FDCSs for electrons with energies of $E_{el} = 8 \pm 2$ eV ejected into the scattering plane. In Fig. 1 these FDCSs are plotted for 16-MeV O^{7+} + He collisions for fixed q of 0.5 ± 0.1 a.u. (left panel), 1.5 ± 0.2 a.u. (middle panel), and 4.0 ± 0.5 a.u. (right panel) as a function of the electron emission angle θ_e. The coordinate system is chosen such that the projectile beam direction coincides with $\theta_e = 0$ and the transverse direction of **q** with $\theta_e = 90°$. The arrow in each panel indicates the direction of **q**. For all q a pronounced maximum is seen in the first quadrant (i.e., in the range $0 < \theta_e < 90°$), which for intermediate q reaches into the second quadrant. In accord with common notation, we refer to this maximum as the binary peak. The recoil peak, often observed in the third quadrant, is completely absent in the present data. This we also observed under similar kinematic conditions for other collision systems with large η [17] and it can be explained by higher-order contributions, which for ion impact have a tendency of suppressing the recoil peak. The same trend is found in higher-order calculations on ionization by positron impact, where the recoil peak (relative to the binary peak) is also suppressed by higher-order effects while it is enhanced for electron impact (see, e.g., [29,30]).

In a first-order treatment of ionization from a $1s$ state, such as the first Born approximation (FBA), the binary peak must occur exactly in the direction of **q**. As mentioned in the Introduction, a strong forward shift of the binary peak relative to **q**, as observed in the present data for $q = 0.5$ a.u., was believed to represent a manifestation of pronounced PCI effects. In previous studies of ionization for large η we never analyzed FDCSs for q larger than 1.5 a.u. There we found that the forward shift systematically decreased with increasing q [17]. The corresponding trend (i.e., a decreasing backward shift with increasing q) was also observed in experimental and theoretical cross sections for ionization of He by 250-eV electron impact for $q < 0.7$ a.u. [31]. It was therefore assumed that PCI tends to become less important with increasing q. Indeed, in the present data for $q = 1.5$ a.u. the binary peak occurs very close to the direction of **q**. However, a surprising observation we make when q is further increased: Now the binary starts shifting again in the forward direction and at $q = 4$ a.u. (right panel of Fig. 1) this shift is actually larger than at $q = 0.5$ a.u.

In Fig. 2 the difference in angles between the position of the binary peak in the experimental data and the direction of

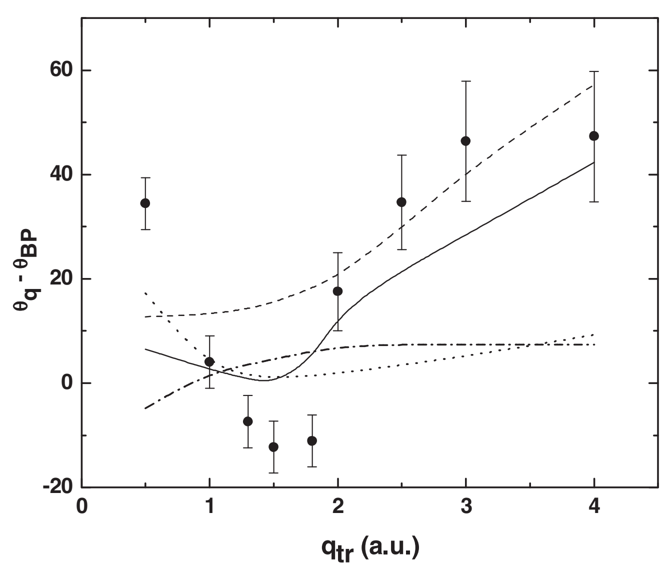

FIG. 2. Forward shift of the binary peak relative to the direction of **q** as a function of q for 16-MeV O^{7+} + He collisions. The dashed curve shows the CDW-EIS calculation, the solid curve the CDW-EIS-PT calculation, the dotted curve the FBA-PT calculation using a Coulomb wave for the ejected electron, and the dash-dotted curve the FBA-PT calculation using a plane wave for the ejected electron.

q is plotted as a function of q. The position of the binary peak was determined from a Gaussian fit. In most cases, it could be fitted reasonably well by a single Gaussian function. However, in some cases, e.g., in the middle panel of Fig. 1, a shoulder on the small-angle wing is present in the data. In those cases, the fit was performed with two Gaussian functions and the position of the binary peak was taken as the centroid of the main peak. A pronounced minimum in the q dependence in the data of Fig. 2 is found around $q=1.5$ a.u. This behavior is rather insensitive to the electron energy, at least in the regime that was covered in our experiment. If, in the case of a two-peak Gaussian fit, the binary peak is assumed to be the weaker of the two peaks, this minimum is shallower, but it is still present. At first glance, this dependence of the binary peak position on q seems to suggest that PCI does not monotonically become weaker with increasing q, but that it minimizes at intermediate q. However, we will demonstrate that such a conclusion would be premature.

Our calculations are based on the continuum-distorted wave (CDW) eikonal initial state (EIS) model. In the operator of the T matrix this model only accounts for the projectile-electron interaction to first order. In this sense it could be viewed as a first-Born-like calculation. However, higher-order contributions in this interaction are treated in the final-state wave function, which is a distorted wave, and in terms of an eikonal phase factor in the initial state. Therefore, both postcollision and precollision effects are considered. Early versions of this approach did not account for the PT interaction (see, e.g., [32,33]), which was later included in terms of the eikonal approximation (see, e.g., [34,35]). Our calculations including the PT interaction, which we label the CDW-EIS-PT model and which are described in detail in [36], are shown in Figs. 1 and 2 as solid lines. Qualitatively, the general trends seen in the experimental data are reproduced by theory. Here too a strong forward shift of the binary peak is observed at small and large q, while at intermediate q this shift minimizes. Quantitatively, there are some discrepancies especially in the angular dependence for $q=0.5$ and 1.5 a.u., where the calculation underestimates the FDCS in the forward direction. Nevertheless, the calculation seems to catch the essential physics reflected in the data.

Notwithstanding the satisfactory qualitative agreement between experiment and theory, we still need to understand the q dependence of the forward shift of the binary peak conceptually. To this end, in the following we will attempt to analyze the ionization dynamics qualitatively. We start by pointing out that such a forward shift cannot occur by multiple interactions of the projectile with the electron only without any other interaction involved. In that case momentum conservation would still demand that the electron momentum has to point in the direction of **q** (ignoring the electron's spherically symmetric initial momentum distribution). Some momentum must be transferred to the recoil ion either by the projectile or by the ejected electron. Therefore, two leading-order sequences of interactions leading to PCI effects are conceivable, as was pointed out previously [37], (a) V_{pe}-V_{et}-V_{pe} and (b) V_{pe}-V_{pt}-V_{pe}, where the subscripts p, e, and t stand for projectile, electron, and target core, respectively. It should be noted, however, that the second sequence represents a simplification because V_{et} is always present, at least in the form of the bond in the initial ground state. The first sequence is different (apart from the absence of V_{pt}) in that V_{et} occurs beyond the bond in the initial state; the electron, now in the continuum, scatters from the residual target ion. For the remainder of this article we will refer to the PCI channels proceeding through the first and second sequences as PCI_{et} and PCI_{pt}, respectively.

The existence of two regions with a large forward shift of the binary peak and of two PCI channels is suggestive that each region can be mostly associated with one specific channel. In order to investigate whether this is indeed the case we once again start with a classical picture to get a better conceptual understanding of the PCI_{et} channel. We consider two different scenarios in which the projectile either penetrates the atom between the electron and the target nucleus or passes the atom outside the electron cloud. In the first scenario the attractive primary projectile-electron interaction would deflect the electron towards but in the second away from the target nucleus. Therefore, one might expect that the PCI_{et} channel is particularly effective in leading to a forward shift at small impact parameters, which in turn favor relatively large q. This would mean that the PCI_{et} channel becomes increasingly important with increasing q. This classical interpretation is supported by our theoretical results. The dashed curves in Figs. 1 and 2 show our CDW-EIS calculations not incorporating the PT interaction. Obviously, this model does not account for the PCI_{pt} channel, but the PCI_{et} channel is still included because the interaction of the electron with the target core (beyond the bond in the initial state) is treated through the final-state wave function. Indeed, in the CDW-EIS calculation the forward shift of the binary peak increases monotonically with increasing q. This shows that indeed the increasing forward shift for $q > 1.5$ a.u. can be associated mostly with the PCI_{et} channel.

In contrast, both PCI channels could contribute to the forward shift at small q and based on the comparison between the CDW-EIS and CDW-EIS-PT calculations we cannot determine which one is more important. Since it is not possible to distinguish between both reaction paths, even interference between both channels could occur. However, in the following we will show that the data can be qualitatively explained without accounting for this interference. In the CDW-EIS-PT calculation the decrease of the forward shift with increasing q for $q < 1.5$ a.u. is qualitatively (but not quantitatively) reproduced. However, it is not clear that in this region the forward shift is entirely due to either of the two PCI channels. This is illustrated by a calculation based on the first Born approximation in which the PT interaction is incorporated within the eikonal approximation and the final state of the ejected electron is described by a Coulomb wave. The results of this model, which we dub the first-Born approximation with PT interaction (the FBA-PT model), are shown as the dotted curve in Fig. 2. Since here the projectile-electron interaction is only treated to first order, neither PCI_{et} nor PCI_{pt} are accounted for. Nevertheless, a decreasing forward shift with increasing q for $q < 1.5$ a.u. is qualitatively reproduced by this model. If, in contrast, the Coulomb wave describing the final-state electron is replaced by a plane wave (dash-dotted curve in Fig. 2), the forward shift in the FBA-PT calculations turns into a backward shift for $q < 1$ a.u. Between $q = 1$ and 1.5 a.u. a slowly rising

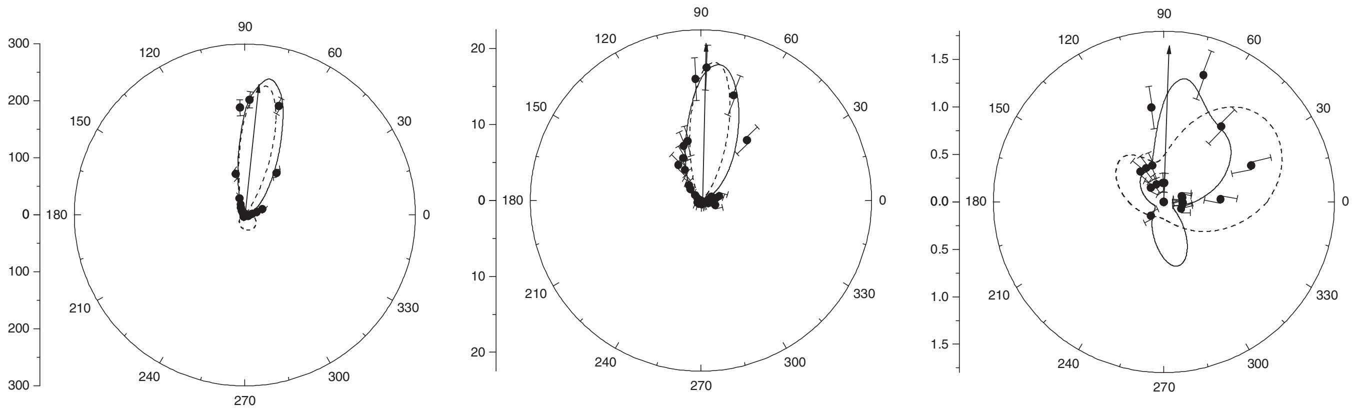

FIG. 3. Fully differential cross sections for target ionization from the 2s state in 24-MeV O^{8+} + Li collisions for electrons with an energy of 8 ± 2 eV ejected into the scattering plane. The momentum transfer is fixed at 0.5 ± 0.1 a.u. (left panel), 1.5 ± 0.2 a.u. (middle panel), and 2.5 ± 0.5 a.u. (right panel). The dashed curve shows the CDW-EIS calculation and the solid curve the CDW-EIS-NN calculation.

forward shift is found and for $q > 1.5$ a.u. a plateau with $\theta_q - \theta_{BP} = 7.5^\circ$ is reached. The effect of using a plane wave is that the interaction between the ejected electron in the final state and the target core is not accounted for. Therefore, the decreasing forward shift with increasing q for $q < 1.5$ a.u. in the FBA-PT calculation can be associated with an interaction sequence (not necessarily in this order) V_{ep}-V_{pt}-V_{et}. In fact, for $q < 1.0$ a.u. the forward shift in the FBA-PT calculation is significantly larger than in the CDW-EIS-PT model, which includes both PCI channels and the V_{ep}-V_{pt}-V_{et} sequence. It is therefore quite possible, contrary to previous belief, that PCI (neither PCI_{et} nor PCI_{pt}) does not play a significant role at small q.

In the region $q < 1.5$ a.u. both the experimental data and the FBA-PT calculations fall off much faster with increasing q than the CDW-EIS-PT results, which is the most comprehensive calculation. This suggests that at small q the role of the PT interaction, relative to PCI, is significantly underestimated by the CDW-EIS-PT calculation. At the same time, the PT interaction tends to decrease the forward shift at large q. Here the CDW-EIS-PT results lie systematically below the measured data, while the CDW-EIS calculation is in good agreement with experiment. Therefore, at large q the PT interaction seems to be overestimated by the CDW-EIS-PT model. Perhaps, some of the discrepancies between experiment and theory could be reduced by accounting for the second electron on the He atom (which in the present model is only considered in terms of screening of the nuclear charge); however, based on our own previous theoretical studies for other collision systems [38], we would expect only relatively small differences.

In Fig. 3 the FDCSs for electrons with $E_{el} = 8 \pm 2$ eV ejected into the scattering plane are plotted for $q = 0.5 \pm 0.1$ a.u. (left panel), 1.5 ± 0.2 a.u. (middle panel), and 2.5 ± 0.5 a.u. (right panel), as a function of θ_e for 24-MeV O^{8+} + Li collisions. Again, the arrows indicate the direction of $\mathbf{q}$. A couple of differences to the data for the He target are quite striking. First, the binary peak is much narrower. Second, there is a much smaller forward shift of the binary peak relative to $\mathbf{q}$ compared to He at small q. In fact, only at the largest q is a clear shift visible. The narrow width of the binary peak simply reflects the small ionization potential of Li and therefore a narrow initial momentum distribution of the electrons. The smaller forward shift at small q can be explained in terms of the larger size of the 2s electron cloud of Li compared to the 1s cloud of He. This means that for Li on average ionization takes place at larger impact parameters, so the interaction both of the electron and of the projectile with the target nucleus, i.e., both PCI channels and the V_{ep}-V_{pt}-V_{et} sequence, are weaker.

In Fig. 4 the forward shift of the binary peak is plotted as a function of q. These data confirm the trend that is indicated already by the FDCSs of Fig. 3: The shift increases slowly but steadily with increasing q. An interesting difference to the data for the helium target is that no decrease of the shift with increasing q is observed for small q. The overall q dependence for the lithium target suggests that here higher-order contributions involving the PT interaction relative to the PCI_{et} channel are much less important than for the helium target. This interpretation is once again supported by our calculations shown in Figs. 3 and 4 (solid curves denote

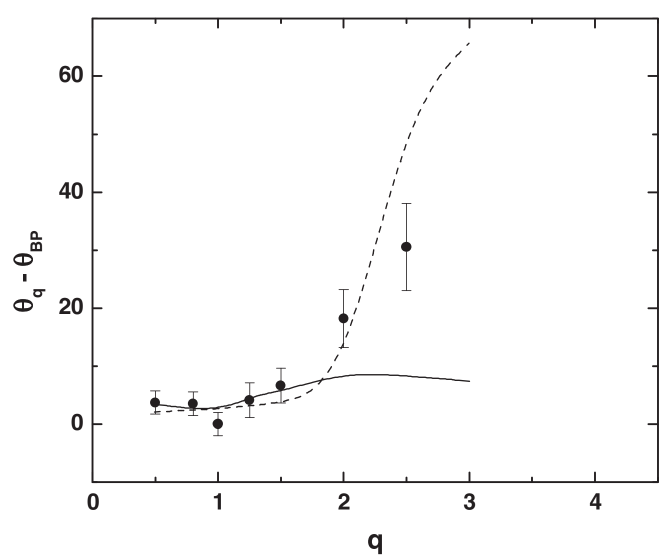

FIG. 4. Same as Fig. 2 but for 24-MeV O^{8+} + Li collisions.

the CDW-EIS-PT calculation and dashed curves the CDW-EIS calculation). Theory is in fair agreement with experiment (except for large q) and the calculations with and without the PT interaction do not differ much from each other for $q < 2$ a.u. As for the helium target the calculation seems to overestimate the role of the PT interaction for large q and the underestimation of the forward shift is even substantially larger than in the helium case. In contrast, at small q this interaction seems to be adequately accounted for.

Another interesting feature in the calculation, probably unrelated to PCI, is that the relatively simple one-lobe structure seen for $q < 2$ a.u. abruptly turns into a rather rich structure at $q = 2.5$ a.u. Shoulders are seen at about $\theta_e = 40^\circ$ and 120° and a separate peak structure near $\theta_e = 300^\circ$. The shoulder structures are not inconsistent with the experimental data; however, the statistical error bars render a definite conclusion impossible. In contrast, a clear splitting of the binary peak into three maxima we observed for a much smaller electron energy ($E_e = 1.5$ eV) at $q = 1.5$ a.u. [39]. In contrast, the peak structure near $\theta_e = 300^\circ$ is not present in the experimental data. It might be tempting to interpret this maximum as the recoil peak shifted in the forward direction by PCI. However, it should be noted that the recoil peak usually becomes weaker (relative to the binary peak) with increasing q. Furthermore, Fiol and Olson [40] argued that a similar peak structure (also seen in the range from 270° to 360° and at large q), which they found in calculated FDCSs for 3.6-MeV/amu $Au^{53+} + He$ collisions, is caused by a different mechanism. While the recoil peak is due to backscattering of the ejected electron from the target nucleus, Fiol and Olson associated the structure found in their calculation with the PT interaction. Since the peak near $\theta_e = 300^\circ$ in our CDW-EIS-PT calculation is not present in the CDW-EIS results it is not inconsistent with the interpretation of Fiol and Olson. In that case the absence of this peak structure in the experimental data would be another indicator that the PT interaction is overestimated in the CDW-EIS-PT model at large q.

IV. CONCLUSION

We have presented an experimental and theoretical study of the postcollision (and precollision) interaction between the outgoing projectile and the ejected electron, as well as other higher-order effects, in ionization of simple target atoms by highly charged ion impact. While previously it was assumed that PCI is particularly important at small q, the present data show strong PCI effects especially at large q. A pronounced forward shift of the binary peak relative to the direction of the momentum transfer $\mathbf{q}$ at small q, observed in the present as well as in earlier data, is probably due to higher-order contributions involving the projectile-target core interaction. Here the PT interaction could be part of a PCI channel that is qualitatively different from the PCI channel mostly responsible for the forward shift at large q since the latter does not involve the PT interaction. However, based on the comparison between experiment and theory we find it more likely that the dominant higher-order mechanism leading to the forward shift at small q does not involve the projectile-electron interaction beyond first order (i.e., PCI). Instead, the interaction of the ejected electron with the target core in the final state plays an important role. For ionization of lithium this higher-order contribution is significantly weaker (relative to PCI) than in ionization of helium.

ACKNOWLEDGMENTS

We thank the MPIK accelerator and TSR team for their experimental support. This work was funded through the Emmy-Noether program of the German Research Council (DFG), under Grant No. FI 1593/1-1. We are grateful for the support from the Alliance Program of the Helmholtz Association, under Grant No. HA216/EMMI. M.S. acknowledges support from the National Science Foundation under Grant No. 0969299. A. B. V. is grateful for support from the Extreme Matter Institute (EMMI) and the DFG under Project No. VO 1278/2-1.

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