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R. E. Olson, W. Schmitt, M. Schulz

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Gesellschaft für Schwerionenforschung mbH
Planckstraße 1 • D-64291 Darmstadt • Germany
Postfach 11 05 52 • D-64220 Darmstadt • Germany

Atoms in Extreme Virtual Photon Fields of Fast, Highly Charged Ions

J. Ullrich^a, B. Bapat^a, A. Dorn^a, S. Keller^b, H. Kollmus^a, R. Mann^c,
R. Moshhammer^a, R. E. Olson^d, W. Schmitt^a, M. Schulz^{a,d}

^a Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Germany

^b Universität Frankfurt, Institut für theoretische Physik, 60054 Frankfurt, Germany

^c Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany

^d University of Missouri – Rolla, Rolla, Missouri 65401, USA

Abstract: Highly-charged ions at velocities close to the speed of light generate strong ($I = 10^{17} - 10^{20} \text{ W/cm}^2$), ultra-short ($t = 10^{-19} - 10^{-17} \text{ s}$) electromagnetic pulses when passing target atoms or molecules. Single and multiple ionization occurs and can be interpreted in terms of photoionization: At small field strength ionization is due to the absorption or the scattering of a *single* virtual photon whereas the incoherent, “simultaneous” absorption of “*many*” field quanta gives rise to multiple ionization in strong fields. In this paper analogies to photoionization are investigated by comparison of kinematically complete experimental data with results of various theoretical calculations for collisions of 100 MeV/u C^{6+} , 1000 MeV/u U^{92+} and 3.6 MeV/u Au^{53+} on He, Ne and Ar targets. Dynamical multiple ionization mechanisms are identified as a function of the momentum transfer. Two-electron final states are found to sensitively depend on the correlated initial state, and the many-particle Coulomb continuum is investigated for triple ionization of neon in super-strong fields.

INTRODUCTION

Ionization by Photons and Charged Particles

It was recognized very early by Bethe (1) that the transition matrix element for excitation or ionization of a target electron by fast charged particle impact is identical to that for photoionization in first order perturbation theory, i.e. for comparatively *weak electromagnetic fields* induced by the ion. In both cases the transition operator is $\exp(i\vec{q} \cdot \vec{r})$ where $\vec{q}$ is the total momentum transfer $\vec{k}_i - \vec{k}_f$ either by the photon (Compton scattering) or by the charged projectile. In the limit of negligibly small $\vec{q}$ approaching the minimum momentum transfer $|\vec{q}| = E_\gamma / c$ by a photon of energy E_γ the matrix element becomes identical to that for photo absorption. For *strong electromagnetic fields*, i.e. at perturbations $Q_p / v_p \geq 1$ (Q_p, v_p : projectile charge and velocity, respectively) Fermi, Weizsäcker and Williams (2) have developed a non-perturbative approximation: The time and impact-parameter dependent field is decom-

posed into two pulses propagating along and transverse to the projectile velocity. Fourier transformation and subsequent quantization yield two pulses of “equivalent” photons carrying a number of $n(\omega)$ photons incident on the atom per unit area and frequency interval $d\omega$. Multiple ionization in strong fields can then be described as the incoherent, “simultaneous” absorption of several virtual photons from the pulse. Both approximations have been widely used in atomic (see e.g. (3-6)) as well as in nuclear physics (see e.g. (7)).

Theoretical interest in the detailed understanding of the equivalence between photon and charged-particle induced ionization strongly increased after precise experimental data on total cross section ratios of helium double to single ionization became available for photo absorption, Compton scattering and ion impact. Charged particle induced dipole transitions at a specific energy loss ΔE_p of the charged projectile have been related to the absorption of a photon with an energy of $E_\gamma = \Delta E_p$, whereas non-dipole transitions have been related to Compton scattering (see (8-10)). Thus, the ratio for charged particle impact could theoretically be derived from those for photons colliding with helium. Most recently, it has even been demonstrated that kinematically complete experiments on double ionization of helium by charged particle impact are feasible (11, 12) opening the unique possibility to explore this fundamental equivalence in unprecedented detail (13).

In this paper kinematically complete data on single, double and multiple ionization are presented for $0.1 \leq Q_p / v_p \leq 4$, i.e. from the perturbative regime where one virtual photon is exchanged to strongly non-perturbative situations described by the Weizsäcker–Williams approximation. Similarities to photoionization are investigated. Evidence is provided that kinematically complete data for charged particle impact covering the entire multi-dimensional final-state momentum space might be advantageous to explore basic questions frequently posted in the past in the context of photo double ionization: Dynamic ionization mechanisms become apparent by investigating differential spectra as a function of the momentum transfer by the projectile $\vec{q}$. Signatures of the initial-state wave function are observed by projecting final-state electron momentum distributions onto a subspace where $\vec{q}$ is negligibly small. Comparison of experimental two-electron momentum distributions with various theoretical model calculations illuminates that the final state sensitively depends on the correlated initial state. Finally, the three-electron – two-ion continuum is investigated for the first time using a modified Dalitz representation for the ejected electrons. On the basis of classical model calculations and auto-correlation functions the question is addressed whether the “simultaneous” absorption of “many” virtual photons in one collision without significant momentum transfer might open the unique possibility to obtain information on the short time correlation of ground state wave functions.

Kinematics

For multiple ionization by fast heavy particle impact it can readily be shown that a negligible amount of momentum $\vec{q}$ and energy (ΔE_p) are transferred compared to the

initial momentum and energy of the projectile (for details see (14)). Then, momentum balances transverse ($\perp$) and longitudinal ($\parallel$) to the projectile propagation can be treated separately and one obtains for multiple ionization without electron transfer (i.e. no mass transfer):

$$q_{\parallel} = (p_{R\parallel} + \sum p_{e\parallel}^i); \quad q_{\parallel} = -\Delta E_p / v_p = -(E_R + \sum U_e^i + \sum E_e^i) / v_p \quad (1)$$

$$q_{\perp} = (p_{R\perp} + \sum p_{e\perp}^i) \quad (2)$$

where E_R is the energy of the recoil ion, U_e^i and E_e^i are the binding and kinetic energy of the i^{th} electron, respectively (atomic units are used: $m_e = \hbar = e = 1$; with m_e : electron mass, e : electron charge, $\hbar$: Planck's constant). At large velocities, close to the speed of light c , the longitudinal momentum transfer approaches the minimum momentum transfer obtained in a photo absorption event: $q_{\parallel} \approx -\Delta E_p / c = -\Delta E_{\gamma} / c$. In general, for fast heavy ion impact, $q_{\parallel}$ is negligibly small, independent of $\vec{q} \approx \vec{q}_{\perp}$ and significant momentum can only be transferred in the direction transverse to the beam propagation (see figure 2).

This leads to important conclusions: First, the signatures of different dynamic mechanisms should manifest themselves in the transverse plane, i.e. in the plane of momentum transfer. Second, the natural direction to study characteristics of the initial state wave function is along the projectile propagation since $q_{\parallel} \approx 0$. This provides the unique possibility to study the role of the initial state simultaneously for all momentum and energy transfers occurring in the collision. This is very different from the situation realized in photoionization experiments where the energy, momentum and angular momentum transfer is well defined. No significant signatures of the correlated initial state have been observed in five fold differential cross sections (FDCS) for photo double ionization of helium.

EXPERIMENT

From the considerations in the previous paragraph it follows that not only kinematically complete experiments are required but, moreover, measurements are desirable that cover the entire multi-dimensional final-state momentum space. This allows one to explore the various questions in subspaces that are ideally suited as outlined above. Recently, we have developed such a device, called the REACTION MICROSCOPE which has been described in detail (14,15). Only the salient features will be summarized here. Ion beams of 100 MeV/u C^{6+} , 1000 MeV/u U^{92+} and 3.6 MeV/u Au^{53+} were delivered by the GANIL, the SIS and UNILAC facilities at Caen and GSI in Darmstadt, respectively. As outlined in figure 1, the given beam was directed on a supersonic, internally cold (typically below 1 K) atomic gas-jet. Recoiling ions and electrons emitted in the collision are guided by homogeneous electric and magnetic fields to multi-hit, position sensitive multi-channel plate detectors, mounted in the longitudinal direction i.e. along the axis of symmetry parallel to the ion beam propagation. From the time-of-flight

FIGURE 1: Outline of the REACTION MICROSCOPE (see text).

(coincidence with each projectile or with the trigger for pulsed ion beams) and the positions of arrival, the initial momenta of the fragments are calculated from the equations of motion for electrons and ions in the well known electric and magnetic fields.

By varying the strength of the projection fields, both the resolution as well as the fraction of the fragments in momentum space that are projected can be chosen over a wide range. Typically, all ions of interest ($|\vec{P}_R| \leq 5 \text{ a.u.}$) are accepted simultaneously.

At the same time all electrons with transverse energies $E_{e\perp} \leq 100 \text{ eV}$ as well as with longitudinal energies $E_{e\parallel} \leq \infty \text{ eV}$ in the forward and $E_{e\parallel} \leq 15 \text{ eV}$ in the backward direction are detected in a typical experiment. Up to ten hits on the electron detector are accepted for a minimum time between two hits of 10 ns in case that both electrons hit the detector in a distance of less than 1 cm. For all other events electrons can be detected on the 8 cm diameter detector even if they hit the detector at identical times.

Thus, depending on the collision dynamics and on the exact electric and magnetic fields chosen in the specific experiment the REACTION MICROSCOPE simultaneously monitors between 60 % (100 MeV/u C^{6+}) and 90 % (3.6 MeV/u U^{53+}) of the twelve-dimensional final-state momentum space for double ionization. Care has to be taken especially if the data are compared to theoretical results. Though achieving large momentum acceptance in general, certain areas are not seen at all by the MICROSCOPE which might generate artificial structures. Usually projections are used, where the limitations are clearly visible or, for more difficult situations, the experimental acceptance is taken into account by folding it into the theoretical calculations.

Superior momentum resolution of $\Delta|\vec{P}_e| = 0.01 \text{ a.u.}$ corresponding to an energy resolution of $\Delta E_e = 1.4 \text{ meV}$ for electrons close to zero energy in the continuum is achieved. Thus, doubly differential cross sections are obtained for the first time in a regime that is notoriously difficult to reach for conventional electron spectroscopy, i.e. using electrostatic analyzers (see e.g. (17)). No principle limitations in resolution are at hand down to energies of a few neV.

RESULTS

Investigations of multiple ionization by charged particle impact using REACTION MICROSCOPES offer the unique possibility to explore dynamic many particle quantum systems for “all” (see above paragraph) momentum and energy transfers in *weak* fields (exchange of one virtual photon) as well as in *super-strong* fields where many equivalent photons are exchanged “simultaneously”, within less than attoseconds (10^{-18} s). Both situations have not been accessible up to now in experiments at third generation light sources or using ultra-fast (i.e. 10 femtoseconds) superintense lasers. Thus, basic questions on dynamical mechanisms, on the role of the correlated initial state as well as on the many particle Coulomb continuum can be addressed with unprecedented completeness in domains that are entirely unexplored up to now.

Single Ionization by Exchange of one Virtual Photon

In figure 2, final state momenta of the electron, the recoiling target ion, as well as the momentum change of the scattered projectile ($\Delta\vec{P}_p = -\vec{q}$) are shown for helium single ionization in collisions with 1000 MeV/u U^{92+} projectiles. Exploiting azimuthal symmetry, all momenta are projected onto a collision plane defined by the incoming projectile momentum vector $\vec{P}_p = P_{p\parallel}$ and the momentum vector $\vec{P}_R = (-P_{R\perp}, P_{R\parallel})$ of the recoiling ion. As outlined before, the momentum change of the projectile in the longitudinal direction, calculated from the collision dynamics $\Delta P_{p\parallel} = \Delta E_p / v_p$, is negligibly small (≤ 0.06 a.u.) for typical electron energies $E_e < 200$ eV (more than 90 % of all events). The FWHM of the $\Delta P_{p\parallel}$ - distribution in figure 2 is determined by the experimental resolution (mainly of the recoil ion) and it is about 0.2 a.u.

FIGURE 2: Distributions of the momenta for electrons, the target ions and for the change in projectile momentum projected onto the collision plane (see text) for 1 GeV/u U^{92+} on He single ionization.

Thus, essentially no momentum is transferred to the projectile in the longitudinal direction and even the transverse momentum transfer is found to be small, scattering angles are typically less than 20 nanorad. We therefore trivially rediscover the dynamics for the absorption of a single virtual photon of $E_\gamma = \Delta E_p$ where the ejected electron momentum is compensated by the recoiling target momentum alone (for details and the equivalent photon picture see (4,5,18)). Especially in the longitudinal direction the measured momenta reflect the bound state properties of the helium atom, independent of the transverse momentum transfer.

This has been investigated at lower energies using Ne and Ar targets in collisions with 3.6 MeV/u Au^{53+} . In figure 3, experimental longitudinal electron momentum distributions are shown for different cuts in $P_{e\perp}$ for single ionization of argon (full circles) along with theoretical CDW-EIS predictions (full line, Continuum Distorted Wave – Eikonal Initial State (19,20)). Three striking features are observed in the doubly differential cross sections: First, all distributions are shifted into the forward direction (positive momenta), i.e. electron emission into the forward hemisphere is most likely. This has been observed before (21) and has been attributed to the “post collision interaction” (PCI) with the highly-charged receding projectile that pulls continuum electrons into the forward direction. In figure 2, this PCI is not visible since the perturbation is smaller and, moreover, since relativistic effects contract the longitudinal projectile potential making it “short ranged” and, thus, less effective in the final state (see the discussion in (18)).

FIGURE 3: Doubly differential cross sections $DDCS = d^2\sigma / (dv_\parallel dv_\perp 2\pi v_\perp)$ as function of the longitudinal electron velocity for certain transverse velocity cuts in singly ionizing 3.6 MeV/u Au^{53+} on Ar collisions. DDCS at different $v_\perp$ are multiplied by a factor of ten, respectively. Lines: CDW-EIS theory.

Second, for small transverse momenta a singularity emerges at $P_{e\parallel} = 0$ which has recently been identified as a “target cusp”, i.e. the expected singularity for long ranged potentials (22). Third, structures are identified near $v_{e\parallel} = \pm 0.5 a.u.$ which are well reproduced by the theory (full line). Separate theoretical calculations for electron emission from the $3p_0$ and $3p_{\pm 1}$ magnetic subshells (Hartree–Fock–states), respectively clearly show that the enhancements are related to the nodal structure of the $3p_0$ state (20). The $3p_{\pm 1}$ substates, which are aligned transverse to the projectile direction have only one maximum at $p = 0$ in the momentum distribution and consequently the structure at $P_{e\parallel} = \pm 0.5 a.u.$ does not occur.

In summary, we have provided strong evidence that the longitudinal electron momentum distributions reflect the property of the bound state wave function independent of the momentum transfer, occurring in the transverse direction only. Moreover, since the transverse momentum transfer is small, the leading dynamic single ionization mechanism for fast heavy-ion impact can be identified and might be described as photo dissociation of the target atom in the virtual photon field of the projectile. Finally, precise quantum mechanical calculations beyond perturbation theory are at hand which reliably predict the observed features on an absolute scale.

Double Ionization by Exchange of one Virtual Photon

Dynamical mechanisms as well as signatures of the correlated initial state have been explored for double ionization of He in the perturbative regime for 100 MeV/u C^{6+} ($Q_P/v_P = 0.1$; Q_P : projectile charge) and 3 keV electron impact ($|Q_P|/v_P = 0.07$) in the transverse plane and along the longitudinal direction, respectively. Similarities to photo ionization are highlighted in the plane of the three emerging target fragments.

Dynamical Mechanisms

In figure 4 azimuthal ionized electron angular distributions are shown for large ($q_{\perp} \geq 1.2 a.u.$, figure 4 a) and small ($q_{\perp} \leq 1.2 a.u.$, figure 4 b) momentum transfers, respectively. Arrows indicate the direction of the projectile momentum change $\Delta P_{p\perp} = -q_{\perp}$. Here, we distinguish the electrons by their relative energies.

For large momentum transfer the high-energetic electron (full square) is directed along the momentum transfer whereas the second is emitted isotropically. This strongly suggests a first order process for the emission of the “first” electron followed by the shake-off for the ejection of the second one to be the dominant dynamic mechanism. Accordingly, calculations in the Bethe-Born approximation plus shake-off have been found to be in good agreement with the measured angular distributions of the total transverse electron momentum $P_{\perp} = \sum p_{e\perp}^i$ with respect to the momentum transfer direction $\Phi_e = \angle(P_{\perp}, \Delta P_p)$ as well as with the relative emission angle spectra

between the two electrons for all q (13). Agreement was achieved even by using the most simple Hartree-Fock $1s^2$ initial state wave function and a Gamov factor to account for the final state interaction between the two electrons (for details see (13)).

FIGURE 4: Azimuthal angular distributions of the fast and slow electron at small (a) and large (b) momentum transfers for double ionization of He by 100 MeV/u C^{6+} impact. Arrows: direction of projectile momentum change (negative of the momentum transfer).

For small momentum transfers, being not even sufficient to knock out one single electron by an impulsive binary projectile–electron encounter, both electrons are found to be emitted strongly isotropic (figure 4b). Here, dynamic features being typical for double ionization after absorption of a photon have been observed (13). Reasonable, but significantly worse agreement with theory was reached in this domain which is inherently included in the Bethe–Born approximation. Deviations between experiment and theory are most significant in the ϕ_{12} -distribution (angle between the two electrons) that is expected to be most sensitive on the electron–electron correlation.

In summary, projection of double ionization data onto the transverse plane enabled us to clearly identify the dynamical mechanisms that dominantly contribute to double ionization in the perturbative regime. When the maximum momentum transfer was limited to values below 1.2 a.u., distinct similarities to double ionization dynamics for the absorption of one real photon have been uncovered.

Role of the Correlated Initial State

Having identified the leading dynamical mechanisms, signatures of the initial state are ideally explored along the longitudinal direction in comparison with theory. In figure 5, the electron sum-momentum in this direction is plotted versus their difference in a two dimensional spectrum integrated over all $q_{\perp}$. Strong correlation between the two electrons is found, being most obvious if the $P_{\parallel}^{-}$ -distributions ($P_{\parallel}^{-} = p_{1\parallel} - p_{2\parallel}$)

are plotted for different sum momenta of the two electrons $P_{\parallel}^+ = p_{1\parallel} + p_{2\parallel}$, i.e. if doubly differential two-electron spectra are considered (figure 6). Data are shown for positive $P_{\parallel}^+$ where the limitations in momentum acceptance are small. The only parts of momentum space that are not accepted ($P_{\parallel}^- = 0 \pm 0.1 \text{ a.u.}$) are indicated by the shaded areas. Whereas small momentum differences $P_{\parallel}^- \approx 0$ are strongly favored for small $P_{\parallel}^+$, experimentally one even finds a minimum at $P_{\parallel}^- = 0$ for large $P_{\parallel}^+$.

FIGURE 5: Double differential cross section $DDCS = d^2\sigma/(dP^- dP^+)$ for double ionization of He in collisions with 100 MeV/u C^{6+} . Grey scale is linear. Lines indicate regions of no momentum acceptance.

This is most surprising as the final state repulsion between the two electrons is expected to be most effective if the relative momentum between the two electrons is small. In contrast, significant effects are found at large momentum differences which are in qualitative agreement with the results of calculations in the Bethe–Born approximation plus shake-off (open symbols in the figure).

In figure 6a, theoretical results are plotted for two different initial state wave functions, a product of two one-electron 1s wave functions with an effective nuclear charge (full line) and a Hylleraas wave function accounting for the electron–electron interaction (dashed-dotted line). In both calculations, coming to very similar predictions, the electron–electron interaction in the final state is completely neglected. Inclusion of the repulsion by means of a Gamov–factor yields an even worse overall agreement with the experimental results (figure 6b,c).

Two features are surprising in the comparison with theory: First, inspecting figures 6a and 6b one finds that the effectiveness of the final state interaction sensitively depends on the details of the initial state wave function. For any assumed mechanism leading to double ionization, i.e. shake-off in our case, different parts in relative posi-

tion space between the two electrons might dominantly contribute for different initial state wave functions resulting in different effects in the final state. Thus, the final state interaction might be seen as “magnifying glass” that enlarges tiny, subtle differences in the initial state at relative positions that are dominantly contributing to double ionization. Second, very different from the conclusions drawn for photo double ionization, different initial state wave functions clearly lead to strongly varying results in the final state for charged particle induced double ionization. Thus, as expected, such experiments provide a sensitive tool to explore correlated bound state wave functions. This is probably due to the fact that the wave function is tested for essentially “all” momentum transfers and “all” virtual photon frequencies (note that the relative difference in the prediction of the total helium binding energy between both wave functions is only one percent). For a detailed analysis using a variety of initial states see refs (23,24).

FIGURE 6: Doubly differential cross sections $DDCS = d^2\sigma/(dP^+ dP^+)$ for double ionization of helium by 100 MeV/u C^{6+} impact for various P_1^+ cuts. Full circles: experimental data. Lines: Theory (see text).

Similarities to Photo Double Ionization

Fivefold differential cross sections (FDCS) for photo double ionization of helium are decisively shaped by the Coulomb repulsion of the two electrons in the final state as well as by selection rules and momentum and energy conservation (25). Dörner et al (26) have explored these predictions in the plane defined by the momentum vectors of all three helium fragments. In essence, the features observed by these authors, i.e. a very small emission probability for both electrons in the same (Coulomb repulsion) and opposite directions (conservation of linear and angular momentum as well as parity) with zero probability for $\vec{p}_{e1} = -\vec{p}_{e2}$ are recovered in figure 7 for double ionization of helium by 3 keV electron impact.

Clearly, the patterns found for charged particle impact are less pronounced, since all virtual photon frequencies are allowed and, moreover, since non-dipole transitions contribute that wash out the strict minimum for photo ionization at $\vec{p}_{e1} = -\vec{p}_{e2}$.

In future, experiments for charged particle impact with significantly increased number of coincidence events (factor 50 to 100) should become feasible. They will allow

for an ultimate comparison between photon and charged particle induced double ionization of helium on the level of FDCS for fixed virtual photon energy, i.e. energy transfer by the charged projectile as well as for negligibly small higher order multipole contributions i.e. for minimum momentum transfer realized for “zero” transverse scattering of the fast projectiles.

FIGURE 7: Momentum distribution of electrons in the fragmentation plane (see text) for double ionization of He by 3 keV electron impact. The direction of one electron is fixed along the arrow.

Triple Ionization in Ultra-Strong Virtual Photon Fields

Relativistic charged particles represent a source of virtual photons with unique properties that are not realizable by any present source of real photons. Power densities of more than 10^{20} Watt/cm² are achievable for pulse times of a few 10^{-19} seconds, i.e. sub-attoseconds which are a factor of 10,000 faster than pulses from ultra-short, super-intense femtosecond lasers. The installation of REACTION MICROSCOPES at heavy-ion storage rings will enable multiple ionization studies in completely unexplored time and intensity domains where the removal of many electrons might be described by the “simultaneous” absorption of many virtual photons from the field (4,5).

In figure 8 the momentum vectors of triply ionized Ne recoil ions are plotted together with the vector sum momenta of all three emitted electrons for 3.6 MeV/u Au⁵³⁺ impact. The collision plane is defined as in figure 2. Obviously, even for triple ionization in a projectile velocity regime (12 a.u.) where the equivalent photon picture is not expected to be applicable features typical for photo absorption are observed. As reported previously for double ionization (11) little momentum is transferred at considerable energy transfer leading to an “explosion” of the atom in the field. Due to the large perturbation by the projectile in the final state a strong effect by the PCI is observed dragging each of the electrons along but, at the same time pushing away the Ne³⁺ ions with nearly identical momenta. PCI thus can be seen as a dissociation of the target fragments in the field of the receding ion without any net-momentum transfer to the fragments.

FIGURE 8: Momentum distributions for the Ne^{3+} recoil ion and the sum momentum of three electrons in triply ionizing 3.6 MeV/u Au^{53+} on Ne collisions.

On this basis one might consider to separate the final state interaction from the signatures that depend on the initial state, i.e. the relative momenta and energies between the three electrons, by a transformation into the three-electron center-of-mass (CM) coordinate frame. Implying that all the electrons are influenced by the PCI on the same footing, independent on their momenta in the instant of ionization, such a transformation would lead to a frame where the PCI is not present at all. We have performed such a transformation and plotted the relative energies of the three electrons in the CM system $\varepsilon_{ei} = E_i^{CM} / \sum E_i^{CM}$ (with E_i^{CM} being the CM energy of the i^{th} electron) in a modified Dalitz-plot (27) in figure 9. This is an equilateral triangle where each triple ionization event is represented by one point inside the triangle with its distance from each individual side being proportional to the relative energy of the corresponding electron as indicated in the figure. Only events in the inscribed circle are allowed due to momentum conservation of the three electrons in the CM frame $\sum \vec{P}_{ei}^{CM} = 0$. Numbering of the electrons is achieved exploiting information on their emission angle: Electron 1 is the one with the smallest angle relative to the projectile propagation direction in each triple ionization event, electron 3 the one with the largest angle and electron 2 lying in between.

Obviously, the electron energies are not independent of each other, the many electron continuum explored for the first time experimentally is found to be strongly correlated. There is an increased probability that electron one and three have large energies compared to electron two. Performing nCTMC calculations (n-body Classical Monte Carlo approach; (28)) with the electron-electron interaction not included beyond an effective potential in the initial state these structures cannot be reproduced.

FIGURE 9: Dalitz-plots (see text) for the relative energies of three electrons in the CM-system emitted in triply ionizing 3.6 MeV/u Au^{53+} on Ne collisions. (a): experiment; (b): theory.

One should keep in mind that such calculations have been demonstrated to accurately predict the dynamics of multiple ionization reactions. A similar result has been obtained for double ionization recently and qualitative agreement between nCTMC and experiment was only achieved when the electron–electron interaction was explicitly implemented in the final state. Presently, such calculations are underway and will be presented in a forthcoming, detailed paper (29).

In the light of the results for single ionization by the same projectiles, where the longitudinal electron momentum spectra have been demonstrated to closely reflect the Hartree-Fock initial state wave function (see figure 3) it does not seem to be optimistic to expect that multi-electron momentum distributions might reveal direct information about the correlated many-electron bound state wave function. Moreover, since the target disintegration occurs within attoseconds, i.e. on a time scale short compared to typical revolution times of ground state electrons one might even hope that such experiments will provide direct information on the short-time correlation between the electrons in the initial state.

CONCLUSION

Using our REACTION MICROSCOPE we have performed a series of kinematically complete experiments on single, double and triple ionization of target atoms for fast highly charged ion impact exploring in detail the relationship between photon and charged particle induced ionization processes.

Covering the whole multi-dimensional final state momentum space (within the minor limitations due to finite acceptances mentioned before) such data for the first time offer the unique possibility to project onto any suitable subspace of lower dimension or to transform into any set of desired coordinates where the underlying physics is appro-

priately elucidated. For the investigation of dynamic mechanisms that contribute to single or multiple ionization, the plane transverse to the beam propagation has been identified as an adequate subspace and electron momenta have been projected onto this plane. Similarly, signatures of the initial state wave function are demonstrated to be sensitively reflected along the longitudinal direction, where no significant momentum can be transferred during the collision. Finally, evidence was provided that a transformation into the CM coordinate frame of the emitted electrons in multiple ionization events helps to identify the correlated electron motion even in the presence of strong, disturbing final state interaction with the receding projectile.

On this basis, it was demonstrated that new information beyond results that have been achieved in photo ionization studies might be obtained: For weak fields, where the projectile interacts via absorption or scattering of a single virtual photon, we have shown that longitudinal electron momentum spectra sensitively depend on the Hartree-Fock initial state for single ionization or on the correlated bound state in case of double ionization. Our projection techniques enabled us to explore signatures of the correlated initial state at all momentum and energy transfers, i.e. at all virtual photon frequencies. For strong fields, not yet producible with real photon sources, the transformation into the CM system separates dynamical effects due to the final state interaction of the projectile with the target fragments from the correlated motion of the electrons relative to each other. The three-electron continuum has been found to be strongly structured.

In future, such kind of experiments will become considerably more efficient, detailed and precise using internally cold, sub-nanosecond pulsed, low-emittance and possibly polarized beams in storage rings, from EBIT ion traps or photo-emission polarized electron sources. Experiments are under way to investigate the dynamics of multiple ionization in femtosecond intense laser fields using REACTION MICROSCOPES.

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