Fragmentation of Atoms in Strong Fields viewed with Reaction-Microscopes

R. Moshammer[1,2], H. Kollmus[1,2], S. Hagmann[2,3,4], M. Schulz[5], B. Feuerstein[2], R. Mann[3], A. Dorn[2], D. Fischer[2], A. N. Perumal[2], C. Höhr[2], C.D. Schröter[1,2], J.R. Crespo Lopez-Urrutia[2], H. Rottke[6], C.Trump[6], W. Sandner[6], R.E. Olson[5], J. Ullrich[1,2]

[1]MPI-Heidelberg, [2]Uni Freiburg, [3]GSI Darmstadt, [4]KSU Manhattan, [5]UMR Missouri, [6]MBI Berlin

The interaction of both, highly charged ions and intense lasers fields, with matter or atoms attract increasing interest because of fundamental questions to be addressed and because of the long term perspectives of potential applications. Such applications cover a wide range from inertial fusion driven by heavy ion or intense laser beams to new techniques in material science and medical treatments. These developments rely on a profound knowledge about the interaction of radiation with single atoms and about the dynamical correlation of electrons in ultra-short and strong fields. In this context ionization of atoms in intense fields plays a key role because the coupling between radiation and matter is mediated by the electrons.

Theoretically, in particular the regime of large perturbations is of interest, where the radiation field strongly modifies the atomic states, where it interacts simultaneously with several electrons and where non-linear effects prevail. This puts severe constraints on theoretical descriptions revealing substantial problems in the treatment of the correlated motion of mutually interacting particles under the action of a time dependent force. In spite of these difficulties, successful theoretical approaches have been developed so far for single ionization of atoms by charged heavy-ion impact as well as by intense laser pulses. But, the extension to more complicated situations like e.g. double or multiple ionization has been identified as a key challenge for many-body Coulomb theories.

Experimentally, the recent developments of advanced many-particle coincidence techniques to study atomic fragmentation allow to identify simultaneously the momenta of all reaction products emerging from a single collision with high resolution. These so called reaction microscopes consist of recoil-ion momentum spectrometers combined with an electron analyzer with 4π efficiency and high momentum resolution. They enable experiments on single and multiple ionization reactions of atoms and molecules with unprecedented completeness and momentum resolution (for a review see [1]). Such kinematically complete experiments provide benchmark data for theories and allow for the first time the separation of different mechanisms involved in the ionization process.

In this report we discuss three topics concerning the fragmentation of atoms in the strong fields generated by fast passing highly-charged ions and intense low-frequency laser pulses. The experiments have been performed at the UNILAC of GSI and at the high power laser facility of the Max-Born-Institute in Berlin.

Ultimate Tests of Single Ionization Theories at Strong Perturbations

In a kinematically complete experiment the emission of low energy electrons (E_e < 150 eV) in single ionization of He-atoms induced by 3.6 MeV/u Au^{53+} ion impact has been studied. Using a reaction-microscope [1] the momenta of the recoiling target-ions and of the ejected electrons have been measured in coincidence. In a previous work the electron energy and angular distribution was studied irrespective of the projectile scattering [2]. These double differential electron emission cross sections have been shown to be in very good agreement with continuum distorted wave eikonal initial state (CDW-EIS) calculations. Because of the large perturbation of the projectile ion with q/v = 4.4 (the projectile charge to velocity ratio in atomic units is a measure of the perturbation strength. Perturbation theory usually can be applied for q/v < 1.), a strong postcollision effect has been observed even at very low electron energies. The receding projectile drags the electrons into the forward direction. As a next step in testing theory in more detail, we investigated the electron emission characteristics as a function of the momentum transferred from the projectile to the target atom. In almost all cases the longitudinal momentum transfer (i.e. the component along the beam direction) is very small compared to the transverse direction. This quantity is deduced from the measured vector momenta of the electron and the recoiling target ion using momentum conservation. In this way projectile scattering angles as small as 20 nrad became accessible, enabling for the complete determination of the three particle dynamics in singly ionizing heavy-ion atom collisions.

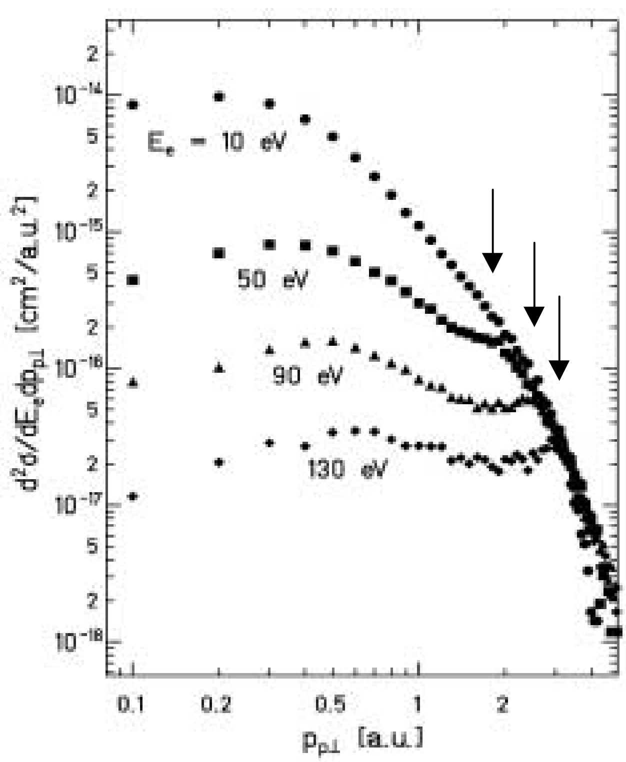

Figure 1: *The projectile momentum transfer in the transverse direction for given electron energies in single ionization of He by 3.6MeV/u Au^{53+} impact. A transverse momentum transfer of $p_{p\perp}$ = 1 a.u. corresponds to a scattering angle of 250 nrad.*

In fig. 1 the distribution of the transverse momentum transfer is shown for fixed ejected electron energies. Low energy electron emission is dominated by small transverse momentum transfers indicating that mainly dipol-transitions from the initially bound to the continuum state contribute [3]. In this so called soft collision regime the fast passing projectile acts much like a source of virtual photons which get absorbed by the target atom revealing similarities with photoionization [4]. With increasing electron energy more violent encounters contribute. Then, the momentum transfer exhibits a peak at a value which is equal to the momentum of the ejected electron (arrows in fig. 1) clearly demonstrating the transition to the binary-encounter regime: the target electron is knocked out in a binary collision with the projectile.

In addition, triple differential cross sections (TDCS) for these highly non-perturbative collisions have been measured. There the angular distribution of the ejected electron in the plane defined by the incoming and the scattered projectile (i.e. in coplanar geometry) is plotted for a given electron energy and for fixed momentum transfer. Such TDCS data are known to be very sensitive on the collision dynamics and they can be considered as the ultimate test of single ionization theories in the non-perturbative regime.

Electron-Electron Interaction in Projectile Ionization: A New Way to Explore (e,2e) on Ions ?

Measurements of differential cross sections for ionization of ions in collisions with high-energy electrons are extremely difficult to perform by applying conventional crossed beams techniques. In essence, due to the low luminosity, such experiments have not been possible up to now, not even in storage rings. If feasible, they would allow for instance high precision momentum spectroscopy of bound states in few-electron heavy-ions.

On the other hand, in a fast collision of a non-bare projectile-ion with a target atom the projectile can be ionized via an interaction with one of the target electrons (electron-electron (e-e) interaction). In those collisions both, the active target electron and the projectile electron, get ionized [5]. This process is equivalent to electron impact ionization of the projectile if the initially bound target electron can be treated as a quasi free electron. In such a scenario, using a dense atomic beam, one would circumvent the above mentioned low luminosity problem of conventional crossed beams experiments. But, there is a second mechanism contributing to projectile ionization: Interaction of the electron with the target nucleus (nucleus-electron (n-e) interaction). Thus, electron impact ionization of ions may be studied in very detail, if the many-particle dynamics is completely controlled experimentally.

Such a measurement has been performed at the UNILAC of GSI studying ionization of 3.6 MeV/u C^{2+} projectiles in collisions with He atoms. In the experiment the final state momentum vectors of all particles emerging from the collision have been mapped. In the following we will demonstrate that a separation of the two competing mechanisms contributing to projectile ionization is indeed possible, because different mechanisms populate kinematically different regions in the final state. If a (n-e) interaction takes place the target nucleus has to deliver the momentum transfer required to ionize the projectile. Thus, one expects a recoiling He^{1+} target ion with large momentum, whereas the target electron acts as a spectator. In contrast, in a (e-e) interaction the target electron plays the active role and the He-nucleus takes part as a spectator [6]. Therefore the two processes ((n-e) and (e-e)) can be separated event by event by putting a condition on the values of the momenta of the target electron p_{ele} and the He^{1+} ion p_{ion}. Selecting only those events, for which $p_{ele} > p_{ion}$ is fulfilled, implies that mainly the (e-e) interaction is left in the resulting subset of the experimental data. The validity of this approach is demonstrated in the fig. 2. There, the momentum distributions of the projectile electron, the target electron and the He^{1+} recoil-ion are projected onto the collision plane. This plane is defined by the incoming projectile momentum and the momentum transfer. As expected for (e-e) interaction, the ionized projectile electrons and the target electrons are preferentially emitted into opposite directions. The target ion behaves as a spectator and therefore exhibits no angular correlation with the emitted electrons.

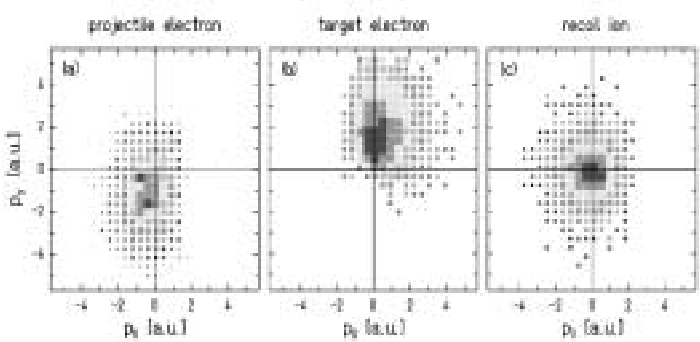

Figure 2: *The momentum distributions of the projectile electron (in the projectile frame), the target electron and the He^{1+} recoil-ion projected onto the collision plane.*

The experimental data are in very good agreement with classical trajectory Monte-Carlo (CTMC) calculations. According to these theoretical results more asymmetric collision partners with respect to the binding energies of the active electrons are required to fulfill the equivalence to electron impact ionization. Such experiments are in preparation and will be performed in near future in the storage ring ESR at GSI using one-electron heavy-ions and light or even excited targets as a dense electron target. Then, as a long term perspective, fully differential cross sections for electron impact ionization of few-electron heavy-ions will become accessible.

Double Ionization of Neon by Intense Laser Pulses

It is almost 20 years ago, that unexpected large yields for the creation of doubly charged ions were observed when atoms are exposed to intense laser fields [7]. This enhancement, termed non-sequential ionization, which can amount to several orders of magnitude, is a consequence of the electron-electron correlation, but the underlying mechanism remained unclear over many years (for a review see [8]). Among many others a classical rescattering model was proposed by Corkum [9] to explain double ionization. In this model the first ionized electron is driven by the electric field of the laser pulse and thrown back to its parent ion knocking out a second electron in an (e,2e)-like collision. Many experimental findings, and in particular recent ion momentum measurements [10,11], favor the rescattering model. But, to ultimately unravel the many-particle dynamics of double ionization in intense laser fields a complete determination of the final state is required, i.e. the determination of the momentum vectors of all atomic fragments. Up to now, such a measurement was beyond experimental capabilities.

We succeeded in performing a first kinematically complete experiment on double ionization of Ne by ultra-short (25 fs) laser pulses (λ = 800 nm) at an intensity of 10^{15} W/cm^2. The created ion and up to two electrons were detected in coincidence using a reaction microscope. In the experiment the momentum vectors of all three particles (electrons and ion) and the charge state of the ion were determined.

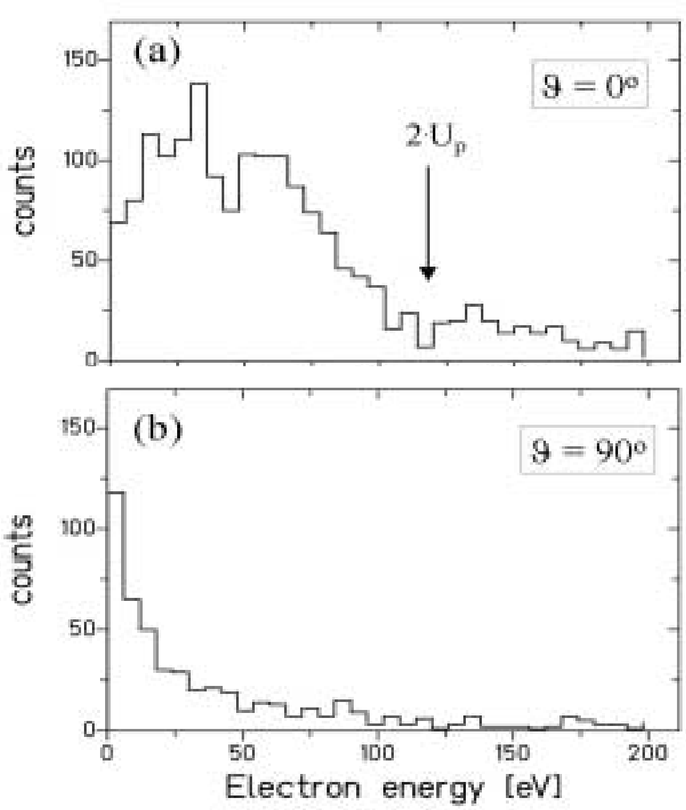

Figure 3: *The electron energy distributions for emission along ($\vartheta = 0^o$) and perpendicular ($\vartheta = 90^o$) to the light polarization axis in double ionization of Ne by 10^{15} W/cm^2 laser pulses.*

In contrast to single ionization, which is dominated by the emission of low energy electrons (E_e < 20 eV), for double ionization high energetic electrons with energies of more than 120 eV have been observed (fig. 3). In both cases electrons are preferentially emitted along the light polarization axis (i.e. along the electric field direction of the laser field). In fact, after being released from the atom the electrons perform a quiver motion in the external laser field. They are driven by the ponderomotive force mediated by the electric field in the light pulse. The final kinetic drift energy of the ionized electron after the end of the laser pulse depends on the phase of the oscillating electric field at which the electron was set free. This energy, which can be as large as $2 \cdot U_P$ (U_P is the mean quiver energy), maximizes if the electron is born at a time when the electric field goes through zero. In the rescattering model for double ionization the (e,2e)-like collision with the returning electron occurs very close to such a zero crossing. Hence, electron energies up to $2 \cdot U_P$ are expected in agreement with our experimental finding. Even though the electron motion is dominated by the ponderomotive force the signature of the (e,2e) collision dynamics is still preserved in the final state. In particular the analysis of correlated two electron spectra, which are not discussed here, yield more detailed information about the fragmentation in strong laser fields.

For the future, experimental studies of electron correlation in strong laser fields will be feasible using a large variety of targets, like e.g. atoms, clusters and molecules. On this road in particular a kinematically complete experiment on helium, the most simple two electron system, remains as an experimental challenge.

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