Atomic Fragmentation in Attosecond Ion-Induced Fields

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Introduction

The recent development of Reaction Microscopes [1] has tremendously widened our possibilities to explore many-electron quantum-dynamics in atomic and molecular break-up reactions under the influence of various time-dependent forces. These „bubble chambers" of atomic and molecular physics allow one to determine the complete vector momenta of several emerging ions and electrons.

One of the most interesting and demanding situations is represented by the collision of a fast highly-charged ion with an atom, schematically depicted in Fig. 1. The fragmentation dynamics, which has been investigated in unprecedented detail within the last two years (see e.g. [2-5] and a review article [6]), though seemingly very crude and violent on first glance, turned out to be exciting for several reasons:

First, due to the large charge and high velocity, huge electromagnetic fields with power densities of up to 10^{20} W/cm^2 are generated by the projectiles giving rise to true, non-perturbative many-electron processes. Up to 40 electrons have been observed to be emitted during such a collision. Second, as illustrated in Fig. 1, large impact parameters b of few a atomic units (1 a.u. = 0.53 Å = $<R_{H(1s)}>$) far outside atomic radii, typically contribute so that the "atom as a whole" with all its electrons is exposed to the field. Third, as a result of the high velocity v > 10 a.u. (1 a.u. = c/137 with c the velocity of light), these fields only act for a very short time. A crude estimate, $\Delta t \approx b/v$, yields typical fragmentation times in the order of attoseconds (10^{-18} s) or below.

In summary, the ion generates an ultra-short half-cycle pulse with a typical transverse field strength Z/b^2 (Z: projectile charge state) strongly exceeding those experienced by electrons in the bound states of light atoms. Since the impact parameters are large, the target atom is essentially dissociated in the field with nearly balancing forces to the target electrons and the nucleus $\vec{F}_e \approx -\vec{F}_n$. Projectile scattering angles as well as the total momentum transfer $\vec{q} = \vec{P}_P^i - \vec{P}_P^f$ are small with a minimum $q_{\min} = q_{\parallel} = \Delta E / \mathrm{v}$ for zero deflection of the beam (ΔE : energy transfer).

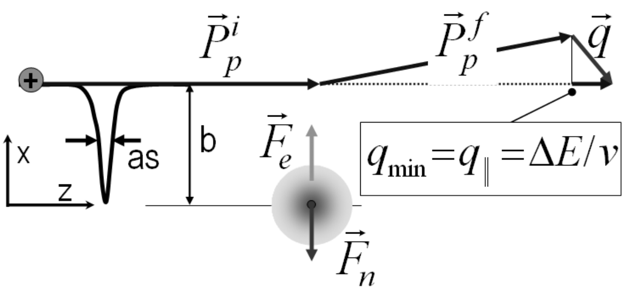

Figure 1: Schematic illustration of a collision between a fast highly-charged ion and an atomic target creating an attosecond transverse half-cycle pulse with power densities up to 10^{20} W/cm^2 being extended over the whole atom.

Results

As an example, in Fig. 2 the fragmentation dynamics is shown for double ionization of helium in collisions with 3.6 MeV/u Au^{53+} ions at a projectile velocity of 12 a.u.. The collision plane has been defined by the incoming projectile propagating from the left to the right and the recoiling target ion momentum vector pointing into the lower half-plane as indicated. Also shown is the sum-momentum vector of both emitted electrons projected onto this plane as well as the momentum change of the projectile. Assuming that the recoiling target momentum is directed along the force $\vec{F}_n$, the collision plane chosen in figures 1 and 2 are identical.

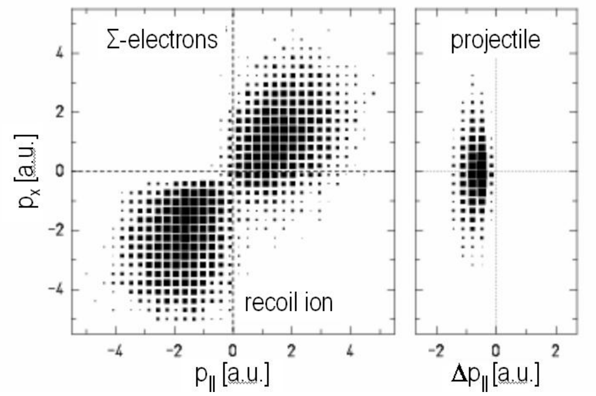

Figure 2: Distributions for the He^{2+} ion momenta, the sum-momenta of both electrons and the momentum change of the projectile in 3.6 MeV/u Au^{53+} on He collisions.

Two prominent features are observed: First, the electron sum- and the recoiling ion momenta are oriented in very good approximation into opposite directions. Even in absolute magnitude the recoil-ion mainly compensates the sum-momentum of both electrons, as can be seen from the relatively small momentum change of the projectile. Thus, the intuitive picture drawn in the introduction, namely that the target atom is effectively dissociated in the attosecond ion-generated half-cycle pulse seems to be quite reasonable.

Second, a strong asymmetry along the forward-backward direction is found, not expected from the above discussion. Electrons are preferentially ejected into the forward direction whereas the He^{2+} ions emerge with negative momenta. This has been observed before and has been interpreted to be a result of the so-called Post-Collision-Interaction (PCI), where the receding projectile pulls the electron behind and pushes the ion away. Again, this can be viewed as dissociation, now proceeding along the longitudinal direction much more slowly, on a femtosecond time-scale.

We might further elucidate the collision dynamics by inspecting the momentum transfers to the individual target electrons. In Fig.3 are shown the momentum distributions of the He^{2+} ion as well as those for each electron in the direction perpendicular to the ion propagation along the x-axes (electrons are distinguished according to their arrival times on the detector which depend on their longitudinal momentum). This is the direction in which the “dissociation force” preferentially acts (note: the x-component of the recoil-ion is always negative by the definition of the coordinate system).

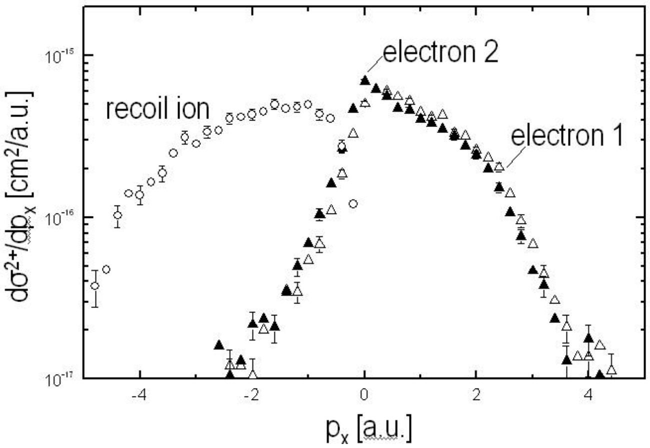

Figure 3: Transverse emission distributions (singly differential cross sections) for the He^{2+} ions and both electrons.

Strikingly, both electrons are found to be strongly correlated with the recoiling ion emerging nearly exclusively into the opposite half sphere. Moreover, electrons “1” and “2” display nearly identical momentum distributions which indicates that the dissociation force acts on an equal footing on both electrons supporting the intuitive picture developed in the introduction, that the attosecond field is extended over the whole atom. Furthermore, a pronounced maximum at zero momentum is observed for one of the electrons as a result of the He^{2+} Coulomb singularity in the final state, giving rise to a “cusp-shaped” electron emission pattern.

While the momentum distributions for both electrons are essentially identical, the tiny difference observed at $p_x = 0$ already indicates that correlations between the two electrons occur. On first glance one might be tempted to expect that correlation plays a minor role in the present situation, where both electrons are ionized individually by independently interacting with the strong, attosecond field of the projectile.

In order to explore electron-electron correlation in detail we have plotted the x-momentum of electron “1” versus the one of electron “2” in Fig. 4. Whereas both electrons clearly tend to emerge into the same sphere due to the directed projectile force, they simultaneously turn out to be significantly correlated in a rather intrigued way. First, at very low momenta, we find the strongest correlation: If one electron has a very small momentum, then the second electron’s momentum is large. At somewhat larger positive $p_x(e_{1,2})$, this feature changes completely and the sum-momentum of both electrons seems to be conserved. At large momenta of either one of the electrons finally, we again observe a significant correlation similar to the one at small $p_x(e_{1,2})$ – if one momentum is large, the other one is small – being most pronounced opposite to the projectile force direction.

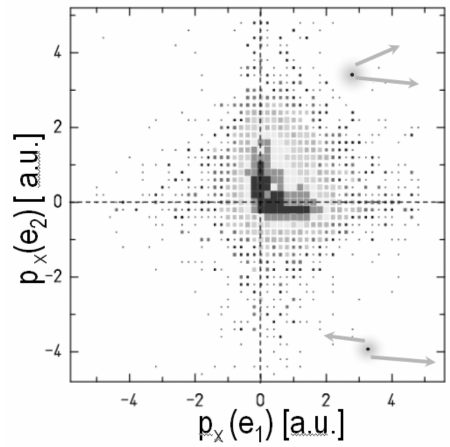

Figure 4: Correlated x-momenta of both electrons.

In order to shed light on the origin of such a pattern one would like to “switch off” the projectile force which might be achieved, by inspecting the correlated momenta in the y – direction (Fig. 5), pointing out of the paper-plane in Fig. 1. Here, neither the attosecond transverse nor the femtosecond longitudinal field (PCI) should occur. Indeed, momenta of both electrons are found to be centred around zero, supporting this assumption and, in addition, are still correlated.

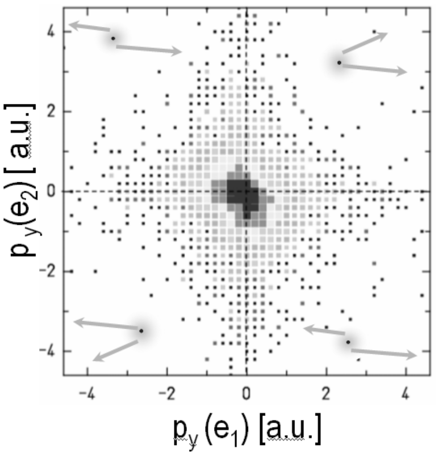

Figure 5: Correlated y-momenta of both electrons.

Now, low-energy electrons tend to go into opposite directions which can most likely be explained by their final state interaction. Still, however, if the momentum of one electron is quite large, the one of the second is surprisingly small, a feature that had even prevailed in the x-direction, in spite of the strong force acting there. We are thus lead to conclude, that this might be a consequence of the initial state correlation of the two target electrons, since, in the “ideal case”, we are now exploring a direction where presumably “no” force occurred during the collision giving us the unique possibility to have a “look” into the atom.

In the future, these experiments shall be performed at higher projectile energies at the GSI experimental storage ring ESR for even larger dissociation forces and shorter pulses induced by U^{92+} projectiles.

References

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