Complete Experiments on Heavy Ion induced Multiple Ionization

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One of the most fundamental reactions in fast charged particle atom interactions is single and multiple ionization of the target atom. Successful theories have been developed for single ionization [1,2], but their extension to the case of double (multiple) ionization turned out to be extremely complicated. State of the art theories are capable to treat double ionization only for very specific and restricted collision systems [3,4], where first order theories are applicable. The theoretical difficulties clearly have their roots in the basic and still unsolved quantum mechanical many body problem.

A decisive experimental breakthrough in atomic collision physics has been established during the last few years by the development of advanced recoil ion momentum spectrometers in combination with completely new and extremely efficient electron detection techniques [5]. These so called "reaction-microscopes" allow to identify simultaneously the momenta of all reaction products emerging from a single collision with high resolution, i.e. to perform kinematically complete experiments [5]. Up to 10 electrons in coincidence with the recoiling target ion can be detected. Three major questions were addressed during the last year:

First: What is the energy loss a projectile ion suffers due to multiple target ionization in a single atomic collision? The answer to this fundamental question delivers the microscopic basis to describe stopping powers of solid matter and biological tissue.

Second: What is the dynamics of the many particle continuum after double ionization induced by heavy ions in the regime of large perturbation (i.e. for a projectile charge to velocity ratio of $q/v > 1$). Whereas the validity of first order approaches and the close relationship to double photoionization facilitate the theoretical treatment at low perturbations ($q/v < 1$) a calculation of the collision system discussed here with $q/v = 4.4$ remains a theoretical challenge. Despite of the relevance at projectile energies close to the maximum of the stopping power our understanding of the collision dynamics in this regime is still rudimentary.

Third: How does an electron with almost zero energy behave in the continuum of two heavy ions ? In the limit of vanishing energy those electrons will stay forever very close to their parent ion and therefore should recombine as a result of the coupling with the radiation field. Thus, the question arises, what is the minimum kinetic energy an electron requires to escape from the target atom?

<u>Energy loss in multiply ionizing collisions</u>

The damage of electronic circuits by cosmic rays, structural and chemical bulk modifications, ion-track formations, surface modifications and medical treatments (cancer therapy) are only a few examples of important nowadays applications based on fast ion matter interactions.

Experimental data on the elementary atomic processes extracted from collision experiments in the gas phase establish the microscopic basis to predict energy loss, straggling or bulk damage in fast-ion matter interactions. But, there are additional difficulties arising due to the high density of solids, the so called solid state effects. Among many other quantities like charge exchange and projectile excitation probabilities, the impact parameter range for ionization of target atoms, which is the dominant contribution to the stopping power, might be considerably changed inside a solid. There are good reasons to assume that impact parameters smaller than the lattice spacing, i.e. a few atomic units, contribute mainly because atoms further away from the ion track are shielded to a certain extent by intermediate layers. At those impact parameters atoms are dominantly multiply ionized in the strong field of the passing fast and highly charged projectile. Hence, impact parameter dependent data sets on single and multiple target ionization in fast-ion atom collisions are required to describe the energy loss of fast ions in solids on a microscopic level.

Using the reaction microscope kinematically complete experiments on single, double and triple ionization of atoms have been performed for the very first time at GSI [6]. A beam of 3.6 MeV/u Au^{53+} has been directed onto a supersonic Ne gas target and the momentum vectors of up to three electrons together with the momentum and the charge state of recoiling neon ions emerging from a single collision have been registered in coincidence with projectile ions, which did not change their charge state.

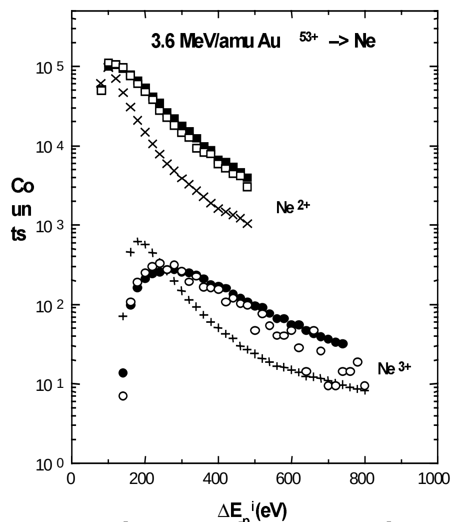

Figure 1: Projectile energy loss spectra due to double and triple ionization of Ne . Open symbols represent the directly measured data (see text).

This way the complete multi dimensional final state in momentum space up to triple ionization has been measured.

In case of higher degrees of ionization a subset of three electrons from all emitted electrons was analysed. Only a very small subset of the overwhelming information contained in the experimental data set has to be considered in order to extract the projectiles energy loss due to multiply ionizing collision. It is obtained from the sum of the continuum electron energies and the Ne ionization potential for the removal of the corresponding number of electrons. Alternatively, it can be extracted from the many particle longitudinal momentum balance under the condition, which is well fulfilled here, that the energy loss is small compared to the total projectile energy.

In fig. 1 the experimental energy loss spectra for double and triple ionization are shown (open symbols). Additionally plotted are energy loss spectra obtained on basis of the independent electron model (crosses). Here, the measured electron energy spectrum for single ionization was convoluted two or three times, respectively, with itself to extract the energy loss spectrum. Obviously, the independent electron model is in poor agreement with the directly measured data. This is mainly because this model does not account for closer collisions dominating in multiple compared to single ionization. The closed symbols in fig. 1 display the energy loss obtained from a similar convolution procedure. However, here the electron energy spectrum of a single electron measured in coincidence with double or triple ionization, respectively, instead of the one for single ionization was convoluted with itself.

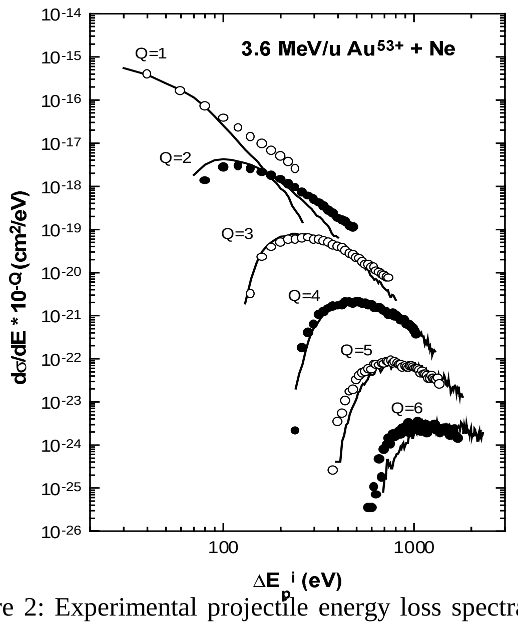

Figure 2: Experimental projectile energy loss spectra due to Q-fold target ionization in comparison with CTMC calculations (full line).

This model accounts partly for both electron correlation effects and the requirement of closer collisions with increasing degree of ionization. This model is in excellent agreement with the directly measured data for double and triple ionization. Since this average electron model works so well for double and triple ionization it is reasonable to assume that it also provides an adequate description for higher degrees of ionization. The result is shown in fig. 2 for charge states 1+ to 6+ in comparison with n-body Classical Trajectory Monte Carlo (nCTMC) calculations, the only theory presently at hand to predict differential cross sections for multiple ionization in atomic collisions.

Our results demonstrate that it is sufficient to measure only one electron out of many emitted electrons in a multiply ionizing collision in order to extract the correct energy loss spectrum. With still continuing data analysis it should be possible to gain information about the impact parameter dependence of multiple ionization. This would allow to establish a direct link between the energy loss in solids and data obtained in atomic collision experiments. Furthermore, our data revealed a strongly correlated motion of the three continuum electrons emitted in triply ionizing collisions which can not be discussed here.

The dynamics of He double ionization

In recent kinematically complete experiments on double ionization of He by impact of 1 GeV/u U^{92+} [7], 100 MeV/u C^{6+} [3] and fast electrons [8] the relationship between charged particle and photon induced ionization has been studied in detail. These pioneering experiments uncovered, depending on the projectile properties, in a very clean manner the similarities and the differences between photon and fast ion induced ionization: Under certain conditions the fast projectile has been interpreted as an extremely strong and ultra-short electromagnetic pulse. Furthermore, it has been concluded that the observed strongly correlated two-electron continuum is a direct image of the correlated atomic initial state [9,10]. Quantum mechanical calculations supported these interpretations of He double ionization by fast ion impact [4]. During the last year we extended this series of double ionization experiments to projectiles with the highest perturbation strength q/v available. The accelerators at GSI offer the exceptional possibilities to deliver such beams. Under these extreme conditions the theoretical treatment is considerably more complicated because higher order effects have to be included and calculations based on first order approximations are not adequate. Our experimental data support this statement in a sense that the receding projectile strongly perturbs and influences the two-electron continuum. This is in contrast to double photoionization or charged particle induced ionization in the regime of low perturbation where the projectile is either simply not present in the final state or where the influence of the receding projectile on the continuum electrons can be neglected.

Choosing an appropriate representation the influence of the outgoing projectile on the two emitted electrons is clearly seen in the experimental data. In fig. 3 the differential cross section as a function of the electrons relative momenta and the angle between both momentum vectors is plotted for double ionization of He by 3.6 MeV/u Au^{53+}. The dominance of small angles is a result of the final state interaction with the outgoing projectile (Post Collision Interaction, PCI) pulling both electrons into the forward direction. On the other hand, the counteracting electron-electron interaction prohibits the occurrence of equal energy electrons emitted into the same direction (see fig. 3).

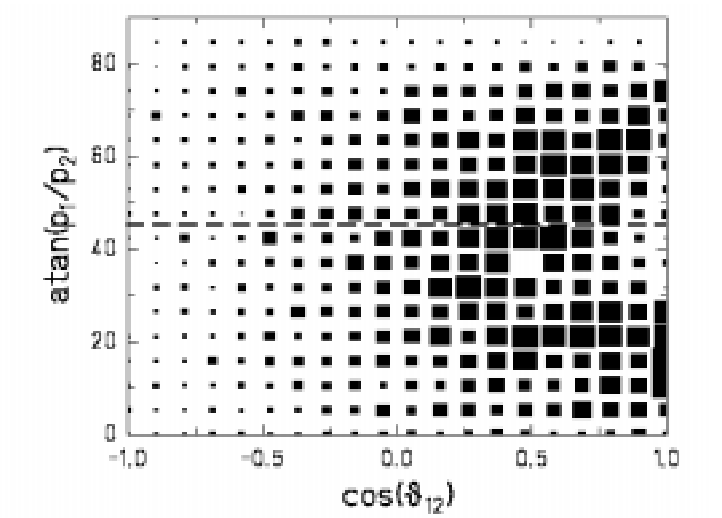

Figure 3: Differential cross section for double ionization of He plotted as function of the electrons momentum ratio and the total angle between both momentum vectors (hyperspherical coordinates). The dashed line represents the case where both electrons have the same energy.

This is just one single aspect of the manifold information that is obtained in such experiments. Double ionization is one of the most simple charged particle induced reaction with two active electrons involved and it is ideally suited to study under very clean and well defined conditions the dynamical behavior of two electrons in the two-center potential of target and projectile. Its investigation is fundamental for the understanding of static and dynamic electron correlations in multi-electron transitions.

Ultra low energy electron emission in He single ionization

Conventional electron spectroscopy suffers from large uncertainties in the detection of electrons with energies below a few eV. Thus, it is not surprising that only very few reliable experimental data on the emission of electrons with energies below 10 eV are available. The regime of ultra low energy continuum electrons ($E_e < 1$ eV) in the Coulomb potential of two nuclei in essence remained unexplored experimentally. Nothing is known on the three particle dynamics at the singularity where the final electron energy is zero: Do these electrons recombine with their parent ion? What is the momentum balance between all three collision partners? Theories predict the cross section differential in electron velocity to diverge like $d\sigma/dv_e = 1/v_e$. This so called electron Cusp peak arises because of phase space arguments with properties depending on the velocity of the projectile and the multi-electron initial state of the target atom. Using our reaction-microscope we were able to study this predicted singular behavior at $v_e = 0$ in the three dimensional velocity space with an energy resolution of $\Delta E_e = 2.5$ meV [11]. This is an improvement of more than two orders of magnitude in comparison to modern conventional electron spectrometers.

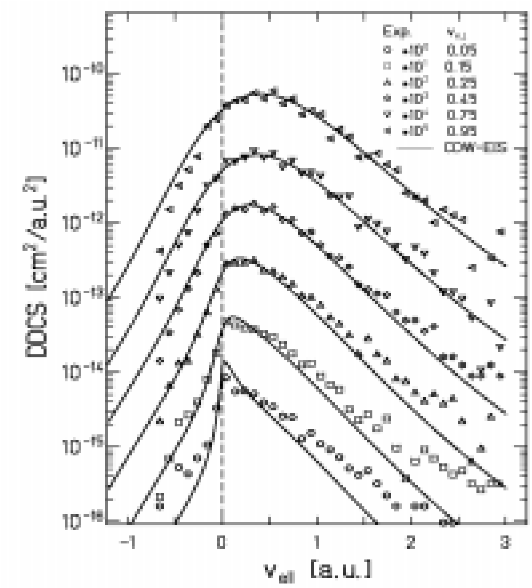

Figure 4: Double differential cross section as function of the longitudinal electron velocity (parallel to ion beam) for certain transverse velocity cuts (perpendicular to ion beam) in singly ionizing 3.6 MeV/u Au^{53+} on He collisions.

In fig. 4 the Doubly Differential Cross Sections (DDCS) for single ionization of He by 3.6 MeV/u Au^{53+} are shown in comparison with Continuum Distorted Wave (CDW) calculations. This represents the up to date most complete map of the soft electron peak arising in singly ionizing collisions. Excellent agreement between theory and experiment is observed in shape as well as in absolute magnitude. Again, a strong forward backward asymmetry is observed which has been attributed to PCI. The emerging highly charged projectile pulls the electrons into the forward direction. A closer inspection of the DDCS (lowermost graph in fig.4) for a transverse velocity cut of only $\Delta v_{e_f} < 0.05$ a.u. (atomic units) reveals a sharp cusp peak centered at $v_{e\|} = 0$ which is still asymmetric and in very good agreement with CDW and CTMC (not shown in the figure) results. The coupling to the radiation field, to account for electron recombination, is not considered in these theories and certainly of minor importance in the energy range studied here. The question arises whether the application of laser or microwave fields might induce transitions from the continuum into bound states, thus burning “trenches” into the cusp peak. This will be verified in future experiments.

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