A.1.5. Two-Electron Continua in Heavy Ion Collisions--*Siegbert Hagmann, Imad Ali, Hans-Jürgen Lüdde* and Elke Wagner**

We find that the angular distribution of electrons emitted for double ionization of the target and detected in coincidence with the charge state of the recoiling ions exhibits a strong enhancement of emission in a narrow forward cone when compared to the angular distribution of electrons recorded for single ionization of the target.

For the differential ionization cross sections under charged particle impact no rigorous restrictions can be derived from conservation laws and so a quantitative description of multiple ionization (MI) does not exist even though a) MI constitutes a much stronger channel for ion induced ionization than in photoionization, and b) MI also increases strongly with the Sommerfeld parameter $s=q_{Proj}/v_{Proj}$ which characterizes the perturbation strength. For collisions where two or more electrons can be emitted into the continuum with a substantial likelihood, only integral MI cross sections have been reported [1] measuring the distribution of charge states of recoiling target ions produced in the collision.

For a thorough investigation of multiple ionization dynamics in the regime of strong perturbations, it is thus imperative to look beyond total cross section ratios and to study differential cross sections for ejected electrons over a wide range of velocities. We place emphasis on extending the range of electron velocities covered to velocities well past the projectile velocity v_{Proj} up to the maximum velocity a target electron can acquire in a binary collision with the projectile $v_{max}=2v_{Proj}$. One original goal of the current experiment was to elucidate the mechanisms for multi-ionization suggested in Ref. 1 for low collision velocities and high incident charge states. There it was surmised — purely on the basis of the velocity dependence of cross section ratios — that two mechanisms may be active in that regime, a two-step mechanism where the projectile interacts with each of the target electrons separately, called TS2, and a mechanism, called TS1, where the first ionized electron interacts with the second in a binary collision.

In the present experiment we focus on strongly perturbing collisions with Sommerfeld parameters $s=q_{Proj}/v_{Proj}>1$, where double ionization is comparable to single ionization.

Beams of $F^{8+,9+}$ and I^{23+} projectiles with collision energies between 0.35AMeV and 1.5AMeV collimated to an area <1 mm^2 over a distance of 4 m traverse the target zone situated inside an electrostatic toroidal electron spectrometer. Electrons emitted in the target zone in a plane containing the beam trajectory (azimuth $\varphi=0^{\circ}$) and with polar angles $\theta=0^{\circ}$ to $\theta=\pm180^{\circ}$ with respect to the beam direction are energy analyzed in the toroidal electrostatic electron spectrometer and detected with a channelplate detector equipped with a 2D position sensitive wedge and strip anode [2]. Recoil ions are extracted from the target zone using a fast pulsing technique.

The strong increase of the ratio of total recoil ion production cross sections $r=\frac{\sigma(He^{2+})}{\sigma(He^{1+})}$ over orders of magnitude observed [1] for charged particle impact ionization with increasing perturbation strength q_{Proj}/v_{Proj} has stimulated a great number of theoretical and experimental endeavors on many-body effects in charged particle induced- and photo-ionization [3-6]. However, the electron spectra corresponding to the underlying single (SI) and double (DI) ionization processes of He had never been investigated directly before Ullrich *et al.*, using a reaction microscope [7,8,9]. In these studies they focus on distant collisions which constitute the dominant part of the total ionization cross section; they observe only very low energy electrons with $E_e \leq 100$eV and $v_e/v_{Proj} \ll 1$. This corresponds, however, to a small fraction of the volume in momentum space covered in the present experiment, since in strongly perturbing collisions a significant fraction of the total ionization cross section produces electrons with $v_e \approx v_{Proj}$.

In Fig. 1 the momentum space doubly differential cross section DDCS $d^2\sigma/dv_e d\Omega_e$ for electron emission in coincidence with He^+ and He^{2+} recoil ions is shown. Electrons with velocities between v=0.64 a.u. and 8.5 a.u. and emission angles between $\Theta=0°$ and $\Theta=180°$ are shown. It is illustrated how the relative contribution of electrons at threshold with $v_e \ll v_{Proj}$ in spectra coincident with He^{2+} changes drastically compared to spectra coincident with He^+ for a perturbation strength $q_{Proj}/v_{Proj}=1.95$. In pure single ionization electrons around $v_e/v_{Proj} \ll 1$ constitute the dominant share of the cross section and the ECC is an inconspicuous feature. In the electron spectra coincident with He^{2+}, however, the maximum cross section is found around the ECC cusp. This means when two electrons are lost by the He target atom the transfer occurs preferentially to continuum states close to $v_e=v_{Proj}$. The region in momentum space around $v_e/v_{Proj} \ll 1$, i.e. electrons in the continuum with very low momentum relative to the target atom they originate from, apparently is avoided for strongly perturbing projectiles when more than one electron is lost by the target: of all electrons with $v_e/v_{Proj} \ll 1$ the ratio of those electrons arising from double loss to those from single loss is 1:3, approximately independent of the perturbation strength s.

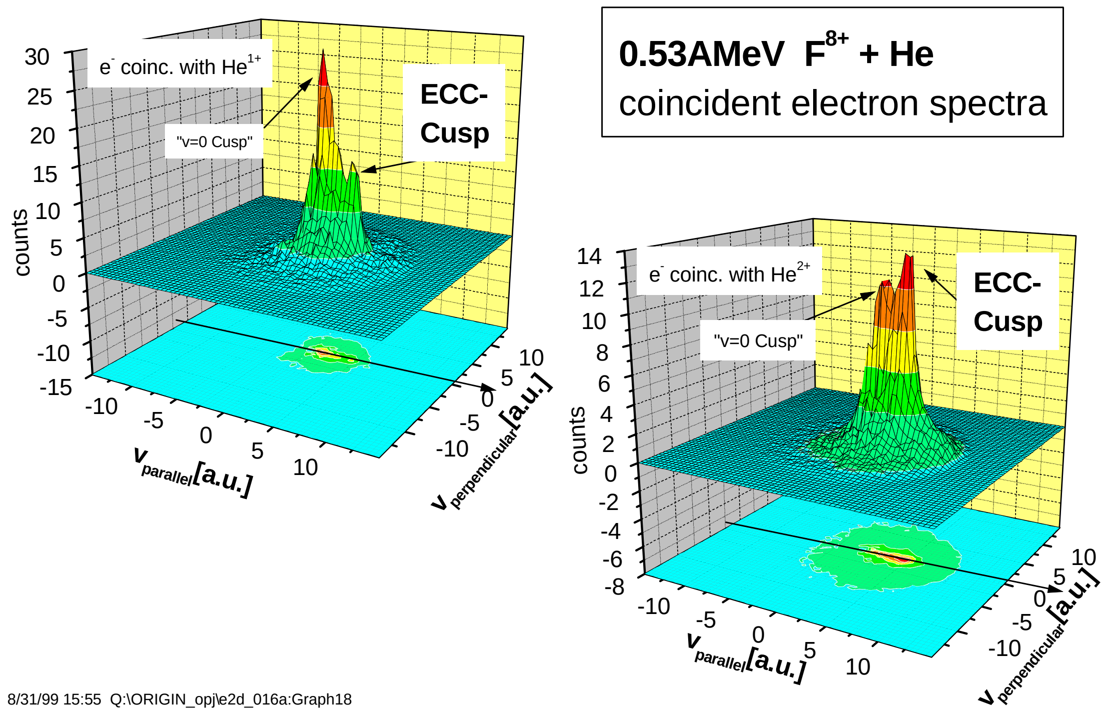

Figure 1. Double differential cross section for electron emissions coincident with He^{2+} and He^{+} for 0.53AMeV F^{8+} impact, q_{Proj}/v_{Proj}=1.95. Both spectra were recorded with a low momentum cutoff of 0.6 a.u.

This is true regardless of the fate of the second electron, be it captured into a projectile bound state or transferred into the continuum. For electrons around the ECC cusp with $v_e/v_{Proj}\approx1$, however, i.e. with small momentum in the projectile frame, the situation is very different: for electrons around the ECC cusp the ratio of those arising from double loss to those from single loss is 1.4. Ratios of the ECC coincident with double to single loss up to 2.7 are seen for the stronger perturbation with the incident I^{23+} projectile.

$\frac{(e^-, He^{2+})}{(e^-, H^+)}$		$s=q_{Proj}/v_{Proj}$		
		1.95	5.0	6.1
v_e/v_{Proj}	<< 1	0.3	0.3	0.3
v_e/v_{Proj}	≈ 1	1.4	2.4	2.7

Table 1. Distribution of electrons coincident with He recoil ions for low electron momentum in the laboratory and the projectile frame, respectively, for different perturbation strength s.

It deserves attention that in double removal of electrons from the He atom the final state is most likely populated in single ionization. Namely the state with the electron removed with the minimum momentum transfer to the continuum threshold is clearly an unlikely final state for either of the two electrons when both electrons are removed from the He atom; the electrons are rather found in the ECC continuum with an apparently much higher momentum relative to the target in the laboratory frame than for single ionization.

In Fig. 2 and Table 1, we compare the collision angular distributions of continuous energy electrons coincident with He^{2+} and He^{+} recoil ions for different perturbation strengths. For swift collisions, v_{Proj}=7.77 a.u and small Sommerfeld parameter s=1.1, we notice the dominance of SI over DI and a nearly constant ratio over almost all emission angles.

For this case (see the lower left diagram in Fig. 2) double ionization (DI) of the target exhibits only a very slight enhancement for electrons emitted in the projectile direction. The electron emission characteristics for close collisions leading to two electrons being ionized from the He atom is effectively not different than that for distant, glancing collisions leading to pure single ionization of He. This aspect of the ionization process changes significantly when s increases while keeping the projectile charge almost constant: for 0.53AMeV (v_{Proj}=4.62 a.u.) F^{8+} projectiles, DI under 0° is almost as strong as SI, and DI has nearly a constant ratio (r≈0.3) for all other angles. When increasing the collisions' strength further to s=5.0 while keeping the collision velocity (v_{Proj}=4.62 a.u.) constant but using incident I^{23+} projectiles, DI is now strongly enhanced over SI in the forward cone $\theta_e = 0° \pm 30°$. At backward angles, though, the ratio is only marginally larger than for 0.53AMeV F^{8+}.

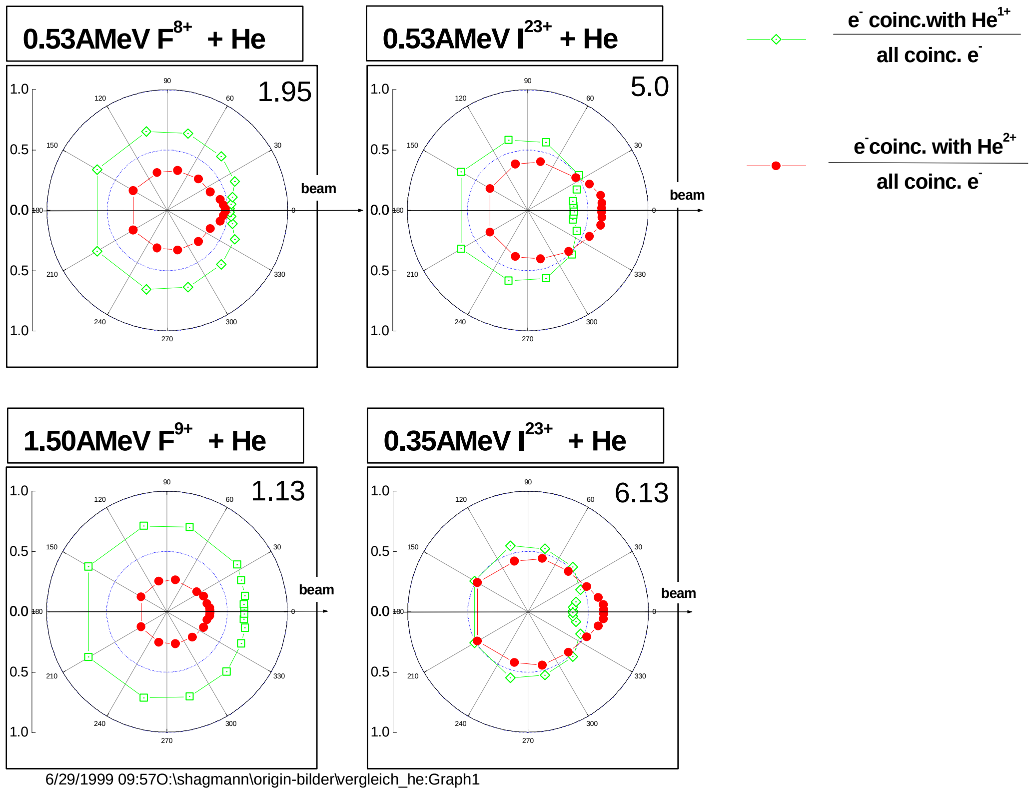

Figure 2. Angular distribution of electrons coincident with He^{+} and He^{2+}: ◊ = (e^{-},He^{+})/all coinc. electrons and ● = (e^{-},He^{2+})/all coinc. electrons for 4 collisions systems with Z_P/v_P between 1.1 and 6.1.

When increasing the Sommerfeld parameter Z_P/v_{Proj} to s=6.1 by decreasing the collision velocity to v_{Proj}=3.75 a.u. for the same projectile I^{23+}, the double-to-single ionization in the forward cone will not increase further, but now DI/SI will increase at angles θ_e » 0° to almost 1.0.

We notice that electrons with $v_e \geq v_{Proj}$ are more than twice as likely to originate from He^{2+} than from He^{+}, i.e. more than could be expected from a reasoning based on electron numbers. This contrasts sharply with the finding that at low electron momenta (v_e « v_{Proj}) electrons from SI are strongly favored over electrons from DI. That is, electrons from DI (or MI) are disfavored at v_e « v_{Proj} for almost all angles except in a very narrow forward cone around the projectile axis. The strong continuum capture channel with large momentum transfer to the electrons dominates the region of small impact parameter collisions leading to a deficiency of electrons with $v_e \leq v_{Proj}$ for multiple target ionization. The strong capture to continuum at small impact parameters thus creates a zone of avoidance at small electron momenta in the laboratory frame in momentum space.

When integrating the coincident electron spectra over all polar angles we can follow the electron momentum dependence of $r=(e^-,He^{2+})/(e^-,He^+)$ more closely. Even after the integration over all angles there still appears a strong velocity dependent enhancement of the ratio r (see Fig. 3). For small electron velocities the ratio merges with the one for non-coincident He^{2+}/He^+ recoil cross sections for this collision system, indicating that electrons with velocities $v_e< 1$ a.u. constitute the dominant part of the total cross section for producing singly and doubly charged He ions.

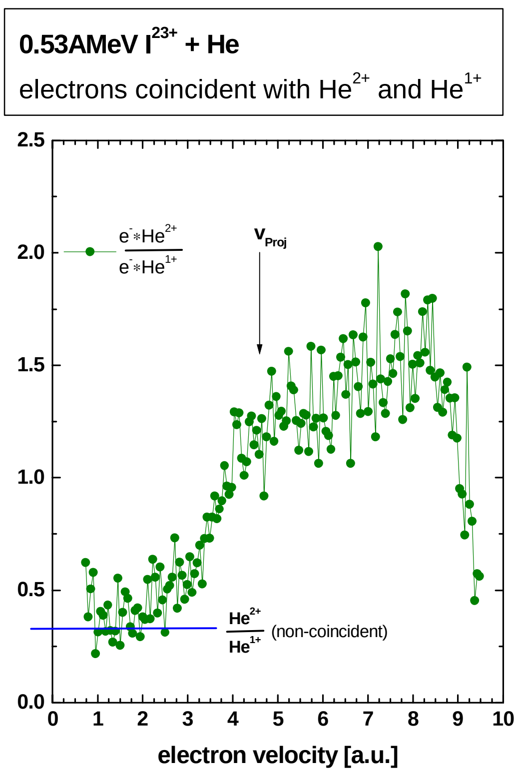

Figure 3. Velocity dependence of the ratio of electrons coincident with He^+ and He^{2+} integrated over all emission angles compared to the non-coincident recoil ion production ratio.

The ratio increases even past the velocity $v_e=v_{Proj}$ and starts to decrease steeply for velocities $v_e\geq 2v_{Proj}$. The velocity $v_e=2v_{Proj}$ is the maximum velocity in the laboratory which a free electron scattered off the projectile by 180° in the projectile frame can acquire in a binary encounter collision of a target electron with the projectile. Close collisions generating doubly ionized He^{2+} at v_{Proj}=4.62 a.u. appear to generate electrons only in a momentum window between ≈2.5 a.u. and 8 a.u. The beginning of the decrease of r as a function of the electron momentum coincides approximately with the maximum of the BE distribution. We therefore conclude that BE electrons generated in close, near head-on binary collisions leading to backscattering of the electron in the projectile frame are not accompanied by shake-off of the second target electron, a process which would transfer it into a low, near isotropic continuum state of the target. Instead, the second electron is either captured into a bound state of the projectile or transferred into a continuum state of the projectile (the ECC or another BE state). This can also be considered as a correlated scattering of a pair of quasi-free electrons in the strong potential of the projectile which results in putting one electron in a state of low momentum and the other in a state of high momentum with respect to the highly charged projectile. The correlated scattering also enhances the chance of a high momentum transfer to one of the electrons [10] — as experimentally seen in the increased cross section for the ECC cusp coincident with He^{2+}. The decrease of r at $v_e \geq$ 8 a.u. indicates that electrons with $v_e \geq 2v_{Proj}$ — which for kinematic reasons cannot arise from classical two-body collisions — arise from collisions where the projectile interacts with the target atom as a whole and where it is more likely that a large momentum is transferred to a single electron without the second electron being affected. First *ab initio* calculations based on quantum statistical techniques confirm the experimental findings.

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*Institut für Theoretische Physik, Universität Frankfurt, Germany.

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