A.1.4 Collective ECC Cusp in Many-Electron Continua in Strong Field Heavy Ion Collisions--*Siegbert Hagmann and Imad Ali*

We have measured doubly differential cross sections for continuum electron emission induced by $I^{23+, 26+}$ and $F^{8+,9+}$ projectiles incident on Ar targets and find that the angular width of the distribution is strongly focussed in the forward direction and is condensing with increasing charge state of the coincident recoil into a "drop" in momentum space around the ECC cusp of electron capture into continuum states of the projectile.

Atomic many-body ionization for charged particle impact has resisted all approaches intended to provide scaling laws of a useful predictive power not just for total recoil ion production cross sections, but in particular for the associated more interesting and more meaningful differential multi-electron continua. Here we present evidence that in strongly perturbing collisions with a large Sommerfeld parameter ($s=q_{Proj}/v_{Proj}$), electrons are very selectively emitted into a narrow cone around the projectile direction. At high emission multiplicities electrons in momentum space are concentrated around the projectile ECC-cusp $v_e=v_{Proj}$, which is inconspicuous for single ionization of the target but then rises to become a prominent feature in the electron spectra of higher multiplicities, its increasing asymmetry emphasizing the high momentum side of the cusp while electron emission with momenta below the cusp appears to be strongly disfavored for higher multiplicities.

Electrons emitted in the target zone in a plane containing the beam direction (azimuth $\varphi=0°$) and with polar angles $\theta=0°$ to $\theta=\pm180°$ 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. Recoil ions are extracted from the target zone using a fast pulsing technique [1].

The simultaneous detection of electrons from all polar angles is illustrated in Fig. 1. It shows the momentum space doubly differential cross section (DDCS) $d^2\sigma/(dv_e d\Omega_e)$ for electron emission for 1.5AMeV F^{9+} (v_{Proj}=7.78 a.u.) impinging on an Ar target; no coincidence condition is applied. Electrons with velocities between v=0.64 a.u. and 8.2 a.u. and emission angles between $\theta = 0°$ and $\pm180°$ with respect to the beam direction are seen. The prominent broad ring with $v_e \approx 4.0$ a.u. consists of Ar LMM satellite Auger lines emitted by Ar recoil ions in various charge states. The projectile Electron Capture to the Continuum (ECC) peak of electrons with very low velocity with respect to the projectile at a laboratory electron velocity $v_e = v_{Proj} = 7.78$ a.u. and $\theta = 0^0$ with respect to the beam direction can also be clearly seen.

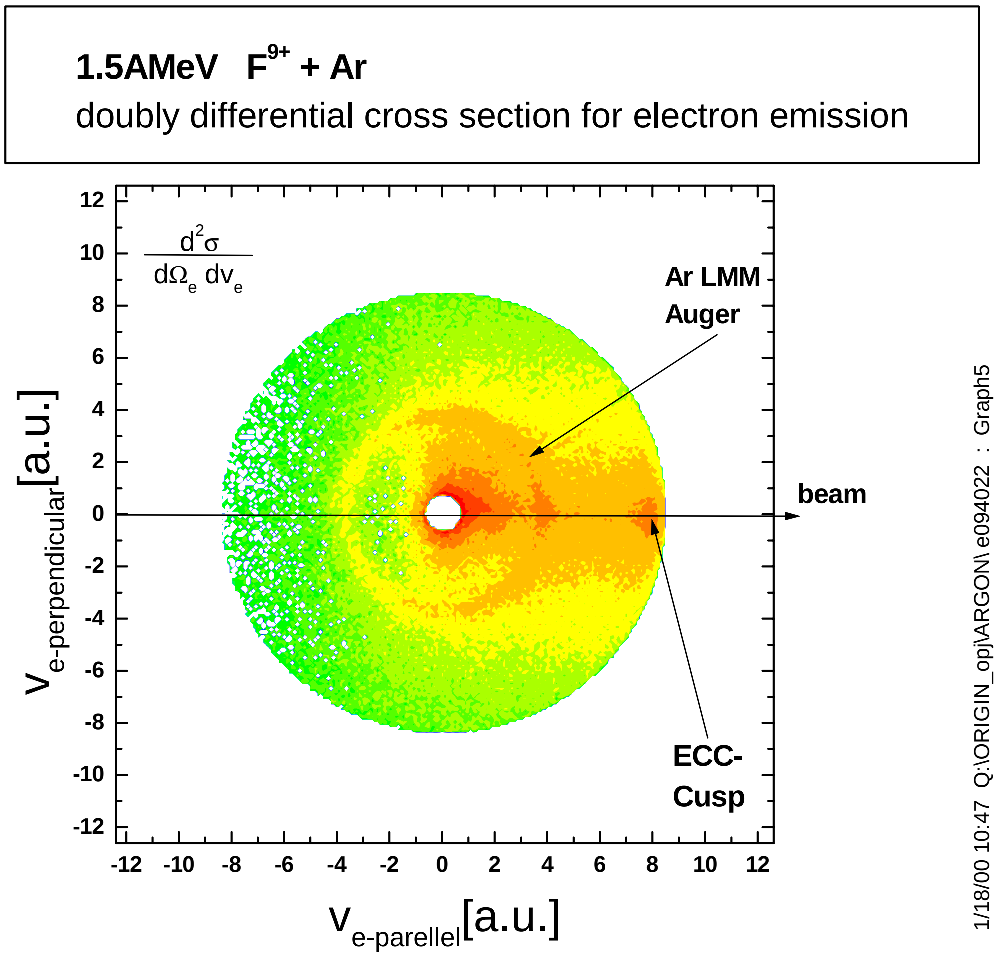

Figure 1. Double differential cross sections for electron emission for 1.5AMeV F^{9+} + Ar for electron velocities between 0.6 and 8.2 a.u.

The ECC cusp of electrons captured into low momentum continuum states of the projectile is the tall, slender peak easily identifiable at $v_{e\|} = v_{Proj}$ and $v_{e\perp} = 0$ in all coincident electron spectra up to those coincident with Ar^{12+} (see Fig. 2). In the spectra of electrons coincident with high recoil charge states most electrons lost by the target and not captured into the projectile bound states have condensed to a drop around the ECC cusp-location in momentum space whose radius is decreasing slightly with increasing number of released electrons down to FWHM ≈1 a.u.

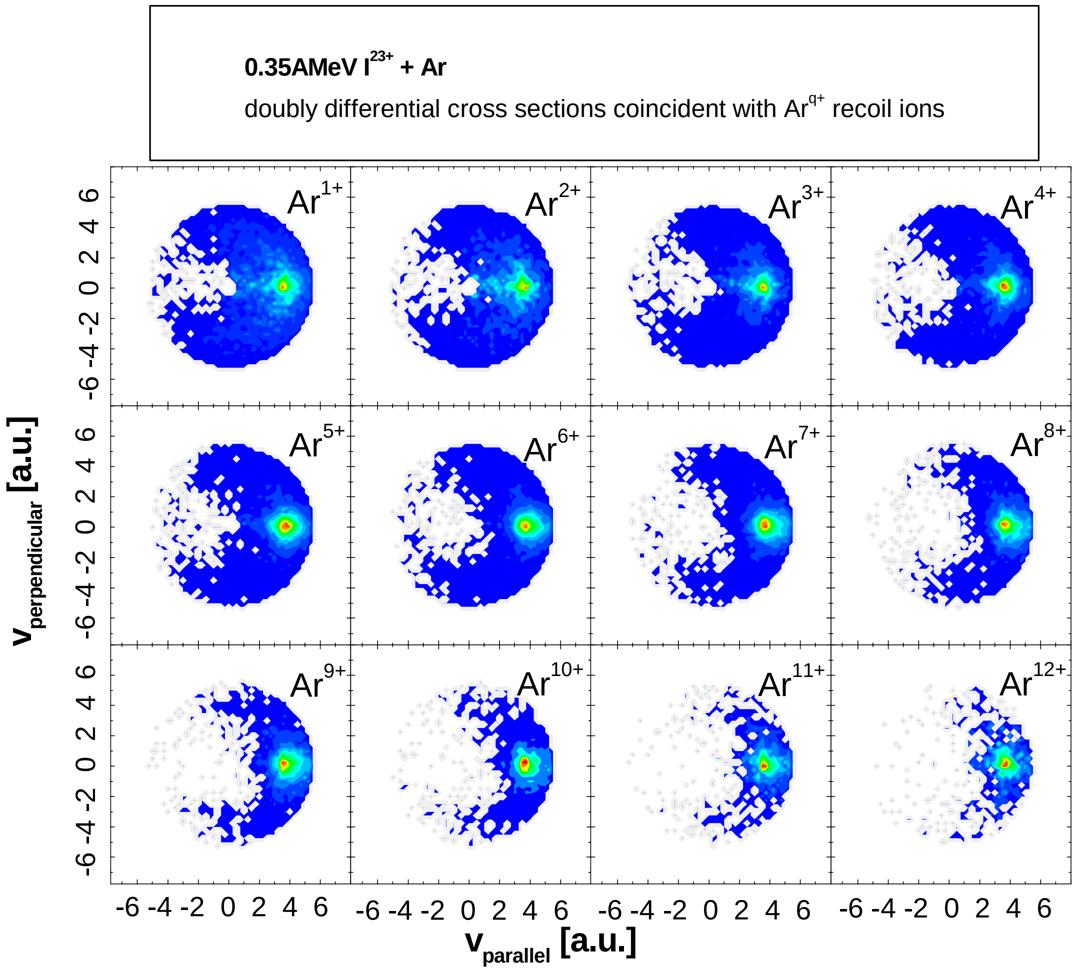

Figure 2. Doubly differential cross section for electron emission coincident with recoil ions in final charge states Ar^{+} up to Ar^{12+} for 0.35AMeV I^{23+} + Ar collisions.

However, multiple ionization dominates the electron continua only in a very narrow forward cone and at high Sommerfeld parameters s; for large emission angles θ≥30° single ionization (SI) dominates the electron continua. The bulk of electrons emitted in high multiplicity is dominantly emitted like a jet into the narrow forward cone. The relative fraction SI contributes to the electron continuum is decreasing with perturbation strength, and the strong increase of the partial multiple ionization (MI) cross section, e.g. (e^{-}, Ar^{6+}), with perturbation strength leads to more electrons being associated with Ar^{6+} in forward emission than Ar^{+} for 0.35AMeV I^{23+}. When comparing SI-electron spectra and MI-electron spectra it is worthwhile to remember the strongly different shape of the spectra: electrons coincident with Ar^{+} dominantly have very low momenta in the laboratory frame peaking at v_e=0, while those coincident with highly charged recoil ions, e.g. Ar^{10+}, are centered around and above the ECC cusp with v_e=v_{Proj}

in the laboratory. This dominance of continuum electrons condensing onto the ECC-cusp seen in the observed variation of the magnitude of the coincident cross section with multiplicity allows a simple argument based on momentum transfer to electrons in the ionization process.

In the incoming channel of the collision, the loosely bound electrons of the target have a momentum $v_e=v_{Proj}$ as seen by the projectile, e.g., typically 4.6 a.u. for 0.53AMeV/u projectile energy.

For a single active electron of the target to be captured into a projectile ECC-continuum state with final momentum $p_e \approx 0$ with respect to the projectile it must undergo a violent collision with momentum transfer [2] $\Delta\mathbf{q}=v_{Proj}$. It is highly unlikely in view of the observed non-monotonic variation of the ECC cross section with the recoil charge state q_R for large perturbation that all these electrons will individually have undergone a high momentum transfer collision with the projectile as is theoretically implied for an independent-electron ECC cusp production. A multiple independent–electron ECC cross section for j electrons should follow $\sigma_j(ECC) \sim 1/(\Delta\mathbf{q}_j)^n$ with $n\geq 2$ and would result in a very steep decrease of $\sigma_j(ECC)$ with j. That is, with recoil charge state q_R, the minimum momentum transfer $\Delta\mathbf{q}_j$ for j electrons out of q_R transferred into the ECC-continuum independently would be $\Delta\mathbf{q}_j=\max(\sum_{i=1}^{j} E_B(i)/v_{Proj}, j*v_{Proj})$, with $E_B(i)$ the binding energy of the i-th electron [3]. $\Delta\mathbf{q}_j$ is obviously increasing with the number of electrons in the continuum at least with $\max(j\bullet E_B(1)/v_{Proj}, j*v_{Proj})$ and so $\sigma_j(ECC) \sim 1/j^2$ at least. This, however, is not seen in the experimental cross sections for large perturbations. In Fig. 3 we compare for selected polar angular sectors the dependence of the coincident electron emission cross section on the charge state q_R of the recoiling target ion for a strong perturbation s=6.13 (with the 0.35AMeV I^{23+} projectile). For a weaker perturbation, we observe a near-monotonous, strong decrease with q_R uniformly in all electron emission angle sectors [1].

It is clearly seen that for the forward sectors up to θ=30° multiple ionization contributes more than single ionization to the relative cross section. The forward enhancement of electron emission with recoil charge state is remarkably strong: the 0°–3° cone intensity normalized to the backward sector 120°- 180° increases monotonically by about a factor 10 when going from Ar^+ to Ar^{10+} (see Fig. 3). All other forward sectors exhibit slightly weaker enhancements for coincident electron emission as can be seen from Fig. 4.

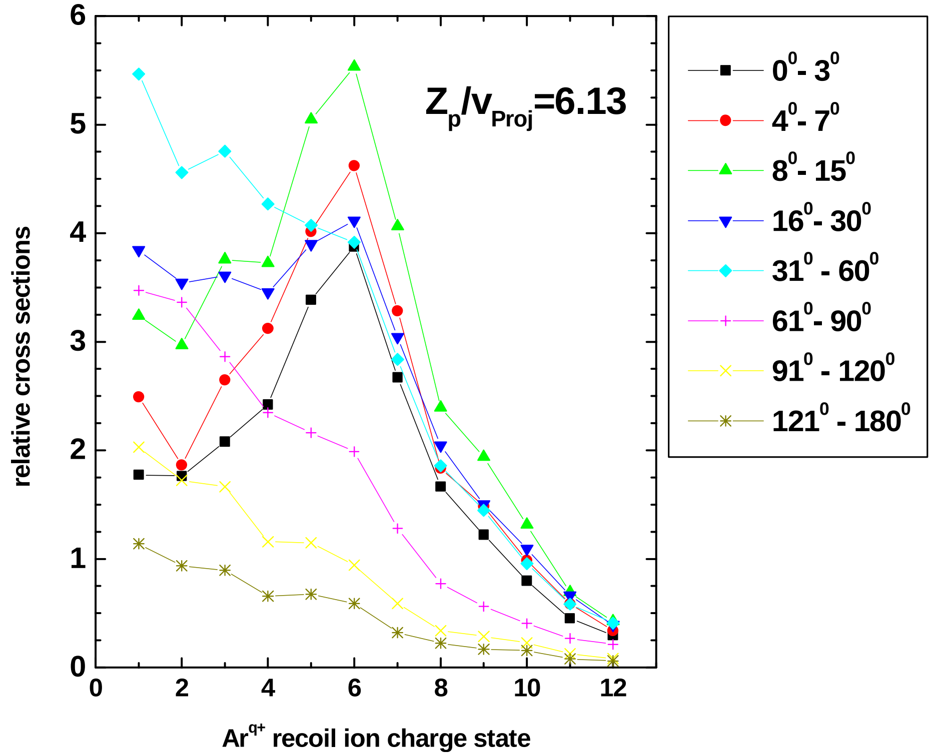

Figure 3. Coincident multi-electron emission in selected polar angle detection windows for 0.35AMeV I^{23+} + Ar as a function of the recoil ion charge state.

The model we tentatively choose to explain the observed data, called "capture cooling", rests on an assumption of a collective interaction of a dense swarm of quasifree electrons interacting in the strong transient potential of the projectile. The elastic scattering of the electrons, which all have an initial momentum centered at $v_e=v_{proj}$ for an observer traveling with the highly charged projectile, leads to some electrons being scattered into states suited for quasi-resonant transfer into bound projectile states (= the "hot" evaporating electrons) while the other electrons end up — as observed — in states of very low momentum with respect to the projectile; these we see as the evaporatively cooled electrons. This model qualitatively explains the apparent lower momentum transfer needed for a multi-electron ECC compared to a one-electron ECC. It is also supported by measurements we have done for the impact parameter dependence of the ECC for F^{9+}+Ne [4,5].

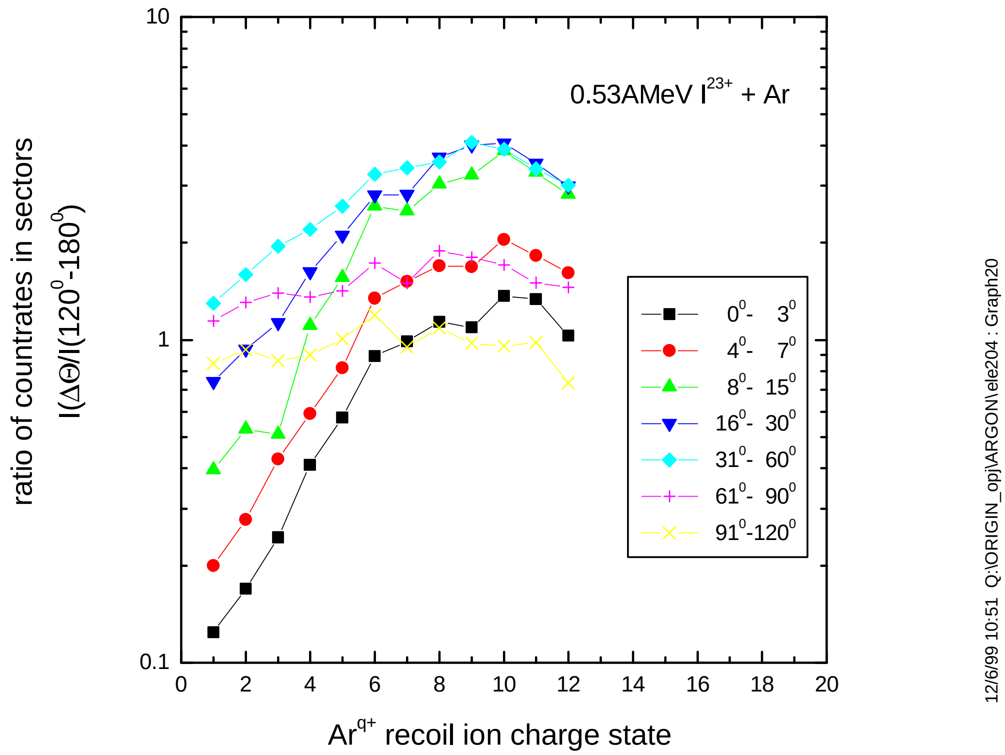

Figure 4. Ratio of count rates for forward sector electron emission normalized to the backward sector 120°-180° for electrons coincident with Ar^{q+} recoil ions for 0.53AMeV I^{23+} + Ar.

We plan to expand this work by using the COLTRIMS technique and determine simultaneously electron and recoil momenta involved in the collision.

References

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