Electron Emission from Projectile Ionization of $U^{28+}$ and $U^{88+, 90+}$ Ions at Relativistic Velocities in Heavy-ion Storage Rings

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We propose to investigate the dynamics of the projectile ionization for multi-electron heavy ions with near relativistic velocities

$$U^{q+} + A \rightarrow U^{(q+n)+} + \{A^+ \} + n \ e^-(\approx 0^0\text{-cusp})$$

by measuring coincidences between electrons in the forward cusp and charge exchanged projectiles. We will compare single and multiple forward electron continua originating from projectiles of relevance for accelerator technology, e.g. low charged $U^{28+}(\ldots 4f^{14}5s^25p^2)$.

The dynamics of forward cusp electron continua generated by few-electron ions, e.g. by Be-like $U^{88+}(1s^22s^2)$ and He-like $U^{90+}(1s^2)$, will also be investigated in order to provide benchmarks for higher order ab initio theories. All corresponding differential cross sections will be measured for targets over a wide Z range from $A=$Hydrogen H to $A=$Xenon Xe.

The differential cross sections for electron emission will permit far more stringent tests for ab initio higher order theories beyond the total cross sections given by first order theories.

I. Introduction and status of the field

Electron emission in many different forms ranging from discrete lines to extended continua was observed to accompany discharges already in the early days of quantum theory; later on - as a more detailed understanding was developing – it was learned to tailor this emission by charged particle or photon impact for extensive systematic studies; the rich information comprised for studying atomic structure and as well collision dynamics quickly generated an intense interest of theorists. Its fundamental importance for the understanding of the mechanism of ionization is most evident in Bethe's and Bohr's treatises on stopping power for ions traversing matter [1, 2, 37].

In the velocity range of interest here, corresponding to beam energies from 1 AMeV to 10 AGeV, the overwhelming contribution to stopping power are (inelastic) collisions of the
swift projectile (in a charge state q) with quasifree target electrons which are ionized into the continuum [26-29].

Remarkably, for non-bare projectiles another contribution to stopping power and beam loss appears; besides the electron continua attributed to target ionization a prominent and strong cusp shaped feature at 0° with respect to the projectile direction and with \( v_e \approx v_{\text{projectile}} \) is observed and is attributed to electron emission from ionization of a projectile carrying electrons, this cusp is normally labelled as electron loss to continuum (ELC) cusp. A splendid example of an ELC cusp measured at CERN is shown in fig. 1 for ultra-relativistic collisions of 160 AGeV Pb\(^{81+}(1s) + \text{Al} \rightarrow \text{Pb}^{82+} + e^- \,(0^0, v_e \approx v_{\text{projectile}})\), where under 0° electrons with \( v_e \approx v_{\text{projectile}} \) ionized out of the 1s shell of the H-like Pb\(^{81+}\) projectile in collisions in the Al target [12] are observed. The shape and width of the cusp are extremely sensitive to details of the collision dynamics[34] and have been subject of intense discussions [23].

![Graph](image)

**Fig.1:** 0° electron loss to continuum ELC cusp originating in 160 AGeV H-like Pb\(^{81+}\)+(1s)+Al collisions. See refs 12 and 23 for discussions of the ELC width. The large peak cross section for the ELC dwarfs the underlying electron continuum in this energy range.

The magnitude of the cross section indicates the relevance this ionization channel has for swift structured projectiles. It so comes as no surprise so see this channel also as the dominant loss rate for multi-electron U\(^{28+}\) beams in SIS and ESR and future FAIR facilities.

For the future accelerator project FAIR high intensity beams of relativistic high Z projectiles like Uranium are envisaged; the needed luminosity of the beam can only be achieved for such ions of high Z when a low charge states q of the ion to be accelerated keeps the space charge limit (\( \sim A/q^2 \)) at a higher level than the one which would be expected for a higher charge state of the projectile [35]. A technically optimal solution for the existing UNILAC accelerator facilities serving FAIR are Uranium beams with a mean charge state 28+ (i.e. \( 4f^{14}5s^25p^2 \)) accelerated to 7.1 AMeV in the UNILAC and then
further in the SIS 12/18 to 50 AMeV. The SIS12/18 needs to inject $1.3 \times 10^{11}$ ions at 2.6 Hz into the SIS100 synchrotron which then provides beams from 400 AMeV to 2.7AGeV for experiments.

As the charge state 28$^+$ of the U beam is nearly over the entire acceleration phase in both synchrotrons far below the average charge state for the near relativistic beam velocity, the dominant beam loss is projectile ionization $U^{28^+} + \{A\} \rightarrow U^{(28+n)+} + \{A^+\}$ with $n \geq 1$; a fraction exceeding 40% has been calculated [8] for multiple loss $n \geq 2$ arising from the large number of weakly bound electrons on the projectile ($E_B = 930$eV for the ionization potential of $U^{28^+}$). Attempts for first order theoretical description of ionization of $U^{28^+}$ in fast collisions ($v_e \ll v_{projectile}$ for outermost electrons) have surprisingly produced mixed results.

In the following we will first show the current status of 1$^{st}$ order theories and then proceed to examples of advanced ab initio theories which also permit to calculate double differential cross sections for electron emission attributed to projectile electron loss; this then will permit a far more stringent comparison with experiment than total cross sections from first order theories.

![Fig. 2: Lifetime of accelerated and stored $U^{28^+}$ - ions in SIS and ESR rings[5]. Data points are compared with calculations in the semi-relativistic RICODE and with the classical CTMC [5]. One has to take into account that the assumed composition of the rest gas contains uncertainties.](image)

A surprising increase of the beam lifetime $\tau = (\rho \sigma v f)^{-1}$ [$\rho$=target density, $\sigma$=ionization cross section, $v$ = beam velocity, $f$ = fraction of ring circumference with target density, $f = 1$ for uniformly filled ring] on the beam energy has been observed (see fig.2) which is partially attributed to a decreasing ionization cross section for the outer electrons in the pertinent collision energy range [3]. Agreement of experimental data with available first order or classical theories is not consistent.
The electron loss cross sections derived from measured lifetimes show a decrease with collision energy. It needs to be taken into account that the assumed composition of the rest-gas used for the calculation of cross sections contains a range of uncertainties.

It is interesting to note that the classical code CTMC exhibits for the ionization cross section a beam energy dependence $\sim E^{-\frac{1}{2}}$, whereas Shevelko's Loss-code and his Ricode applying relativistic 1st Born predict a $E^{-1}$ dependence [5]. The classical calculation misses the absolute cross section but exhibits the slower decrease of the electron loss cross section with increasing target $Z$ from the experimental data as is clearly seen in fig. 3, but only for the $H_2$ target; this may be understood classically from the observation that for a higher $Z$ target electrons over a wider range of binding energies (and thus collision energies) are present and the maximum of the projectile ionization cross section which also depends on the binding energy of the respective electron moves to larger collision energies. This results in a flatter maximum and smoother decrease with collision energy for higher $Z$ targets. This target electron induced contribution to projectile ionization is accounted for ad hoc by separately introduced terms in some first order theories. Such calculations, like the modified Born approximation of Dubois et al. [6], appear then after application of individual fit-factors to reproduce the beam energy dependence for the targets H to Ar (as seen in fig. 4), other than regular first order theories without these corrections (see fig.5). This method does not provide, however, absolute cross sections without using fit factors.

Fig. 3: Cross section for projectile electron loss for $U^{28+}$ in collisions with $H_2$ and $N_2$ for collision energies between 1 AMeV and 120 AMeV [3]; open squares present CTMC calculations, open triangles Shevelko's RICODE, experimental data are full symbols.
Fig. 4: Experimental electron loss cross sections for $U^{28+}$ on various targets compared to a modified Born procedure (full line) [6].

The RICODE of Shevelko (fig. 3 and fig. 5) is better suited than the non-relativistic code but is also rather limited in agreement with the data of fig. 3 and with modified Born approximation of fig. 4.

Fig. 5 Theoretical electron loss cross section for $U^{28+} + A$ as function of ion energy using the RICODE [5]. Note that the energy dependence of the loss cross section is not dependent on the target atom $A$.

Fig. 6: Calculated loss cross section for $U^{28+} + H$ in the asymptotic regime where the calculated collision energy dependence is weak [43], see also fig. 5. The theoretical method used is the relativistic first order Born code LOSS-R. The code predicts the main contribution to electron loss to arise from $4f^{14}$ and not $5s^2p^2$ due to the difference in occupation numbers.
We also note that even the semi-relativistic RICODE (based on a relativistic Born approximation in momentum transfer space, which uses non-relativistic atomic wave functions) is in clear disagreement with fully relativistic calculations[5, 39] for more tightly bound electrons, see fig 7 and ref 6.

Fig 7: Comparison of theoretical 1s ionization cross sections of U$^{91+}$ by protons [6].

First order Born and classical theories are well suited to describe the overall features of experimental lifetimes; total electron emission cross sections are described in certain collisions energy ranges e.g. by the RICODE. These total cross sections are, however, often very insensitive to different approximations made in theoretical calculations; this and the lack of differential cross sections for electron emission limit the predictive power of 1st order theories.

Active role of target nucleus AND target electrons:

Detailed ab initio calculations by A. Voitkiv and coworkers from the MPI-K have repeatedly pointed out deficiencies in first order theories; they emphasize a few key aspects complicating the treatment of ionization of electrons out of the projectile: the atomic target carries electrons and for higher Z targets the atomic field may be too strong for a first order Born approximation; it thus may be indicated to go beyond the first Born approximation- in particular when more than one electron undergoes a transition [19]. Keeping in mind that the electron impact ionization of U$^{28+}$ due to target electrons considered quasifree reaches easily few $10^{-20}$ cm$^2$ to $10^{-19}$ cm$^2$ (per target-electron) [40, and for actual calculated first order loss cross sections see fig 5] in the collision energy range of interest here, a theoretical treatment of projectile ionization encompassing the active role of target nucleus as well as target electrons is indispensable [19]; this is incorporated in the symmetric eikonal model for relativistic ion atom collisions [12, 19]. This ab initio theoretical approach not only provides total ionization cross sections but
also differential cross sections. The eikonal approximation gives at low collision energies a factor 5 to 10 lower total cross sections than the first order theory (see fig 8).

### Projectile Electron Ionization

\[
\text{U}^{91+}(1s) + \text{Au} \rightarrow \text{U}^{92+} + e^- + \{\text{Au}^+\}
\]

Fig. 8: Total cross section for projectile electron loss from \( \text{U}^{91+} \) in collisions with \( \text{Au} \) using different theoretical models [21].

In fig.8 it is illustrated that a fully relativistic approximation for the active electrons considered is essential.

Fig. 9 Electron loss cross section for 105 AMeV \( \text{U}^{90+} \) for various targets. The agreement of experiment with theory is very satisfactory for the eikonal theory (full line), but less so for the first order Born approximation [22].
Comparison of experimental data for 1-electron loss from 105 AMeV U$^{90+}$ +A$_{\text{target}}$ collisions with theory reveals that first order theories drastically overestimate the ionization cross section, particularly at medium and higher A$_{\text{target}}$ whereas the eikonal approximation is in good agreement up to high Z targets. This is seen to also apply for 1s and 2s ionization from U$^{90+}$ and U$^{89+}$ projectiles [22]. The theoretical methods used by ref 22 allow comparing the angular distribution of the ionized electrons with various theoretical models; it is interesting to note that the full relativistic treatment makes the emission of electrons more symmetric with respect to 90°.

A. Surzhykov et al. showed [18] the relative contribution of electrons originating from the projectile 2s and 1s state, respectively, to the ELC cusp shape in the laboratory to be significantly different in the (projectile continuum based) angular and energy distributions. This results in a laboratory width of the ELC strongly dependent on the relative fraction of electrons from 2s and 1s.

**Fig. 10.** Single differential cross section $d\sigma/dE$ for electron ionization out of the projectile in 1AGeV U$^{91+}$ +He with 0% (full line), 10%, 20% and 30% relative population of the excited 2s state. It is apparent that the ELC cusp is significant broader for pure loss from the 1s state, as given by the full line. The abscissa denotes the total electron energy $\gamma_{\text{proj}}mc^2$, where $\gamma_{\text{proj}} = 2$ for the relativistic 1AGeV collision energy; the actual kinetic energy of the cusp electron at the top of the ridge is $(\gamma_{\text{proj}}-1)mc^2$. 

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Fig. 11: The theoretical differential cross sections for the emitted electrons in 90AMeV $^{90}$U$^{88+}$ + $N_2$→$^{90}$U$^{89+}$ + $e^-$ is visibly structured near the continuum threshold and has different shape for higher electron energies [18 and Voitkiv, Surzhykov priv. communication].

The complex non-monotonic dependence of the electron emission in the differential cross section for projectile ionization as appearing in the projectile frame is illustrated in fig. 11. We note that the original contributing angular distributions for electrons of different energies in the projectile frame cannot be retrieved from the single differential cross section for the ELC cusp as e.g. calculated in fig. 10 for 1 AGeV $^{91}$U. This implies that for a stringent test of ab initio theories one has to aim at experimental methods which allow unfolding the double differential cross sections DDCS for ionization of the projectile electron.

Another corresponding experimental ELC cusp representing the single differential cross section $d\sigma/d\Omega$ as electron ridge which summarizes over the low energy part of the continuum is seen in fig. 12 for 300AMeV $^{47}$Sn; however, from such single differential cross sections the theoretical double differential cross section cannot yet be unfolded because the emission direction within the cone of acceptance of the electron spectrometer cannot be retrieved without special provisions.
Fig. 12: Single differential cross section $d\sigma/dp$ for electron emission from projectile ionization for $^{100}_{50}$Sn$^{47+}(1s^22s) + N_2 \rightarrow$ Sn$^{48+}(1s^2) + e_{\text{cusp}}(0^0)$; the ELC cusp is identified via coincidences of the $0^0$ electron with a charge exchanged Sn$^{48+}$ projectile.

In order to provide an appropriate tool for comparison of experiment and theory and to unfold the DDCS in the projectile frame the electron spectrometer must map the primordial vector momenta of electrons at the target zone onto the image plane, where they need to be detected in 2D position sensitive electron detectors.
II. Objectives and methods of investigation for spectroscopy of electron loss from $U^{28+}$

In order to reconstruct in the image plane the vector momenta of electrons generated in an ion-atom collision in the supersonic jet target of the ESR storage ring we have developed an imaging forward electron spectrometer which guides electrons emitted from the target zone under $0^\circ \pm 1.5^\circ$ after magnetic selection onto a 2D position sensitive electron detector behind momentum defining slits (see fig. 13.)

Fig. 13: Imaging electron spectrometer at ESR target zone with a $60^\circ$ dipole, quadrupole triplet, $60^\circ$ dipole. The 2D position sensitive electron detector is positioned behind momentum defining slits. This represents the setup as used for radiative electron capture to continuum RECC cusp and the high endpoint of electron-nucleus bremsstrahlung.

When the spectrometer is operated with reduced momentum slit width and in telescopic mode where the magnifications $|M_x| = |M_y| = 1$, on the 2D position sensitive detector positioned behind the beam waist at the momentum defining slits the primordial vector momenta of the emitted electrons may be reconstructed. We have operated the spectrometer successfully for a study of the radiative electron capture into the projectile continuum and the high energy endpoint of electron-nucleus bremsstrahlung [44]. At that time a conventional quadrupole tripllett was implemented which did not allow true telescopic operation due to slight hysteresis. We have now exchanged the old tripllett for a new iron-free cos2$\theta$ type with a large 150mmØ aperture. In order to permit a higher momentum resolution the electron spectrometer is now also operated with dipoles in the $+60^\circ$/$-60^\circ$ mode. The setup in fig. 13 represents the $+60^\circ$/$+60^\circ$ mode used in the RECC experiment.
We have previously measured simultaneously with the RECC cusp also the ELC cups for
90 AMeV

\[ \text{U}^{88+}(1s^22s^2) + \text{N}_2 \rightarrow \text{U}^{89+}(1s^22s) + e'(0^+, v_e \approx v_{proj}) \]

where the charge-changed projectile \( \text{U}^{89+} \) has lost one electron. The ELC cusp is
identified via coincidences between electrons momentum analyzed with the forward
spectrometer and the charge exchanged projectile \( \text{U}^{89+}(1s^22s) \). The experimental ELC
cusp is shown in fig. 14.

![Fig. 14: Electron loss to continuum cusp ELC for 90 AMeV \( \text{U}^{88+} + \text{N}_2 \rightarrow \text{U}^{89+} + e'(0^+) \). The lower abscissa gives the laboratory electron momentum and the top abscissa gives the electron energy in the projectile continuum.](image)

We point out that already with the very moderate momentum resolution used in the
RECC experiment the electron peak provides access to very low energies in the projectile
continuum.

In the new configuration the improved momentum resolution is expected to resolve
around the peak electron energies of a few eV in the projectile continuum. For every
data point in fig. 14 we will have to accumulate data on the 2D position sensitive anode
for the desired angular distribution: combined with the telescopic operation the
information on the 2D position sensitive detector for every pass-momentum of the
spectrometer will then permit to reconstruct the primordial transverse vector momenta
for a range of energies in the continuum.
In the previously used configuration the angular data on the 2D position sensitive detector could not be used to unfold the DDCS in the projectile frame due to a hysteresis in the old quadrupole triplet, the resulting effects on the mapping could not be compensated to our satisfaction. For this reason only single differential cross sections $d\sigma/dp$ could be derived from the data at that time.

The $DDCS$ for electron emission (as seen e.g. in the theoretical DDCS in fig. 11) is the primordial information on the collision dynamics and provides the most stringent test of advanced higher order theories and their predictive power. Theoretical estimates have indicated for the $U^{28+}$ beam in the ESR in the available collision energy range 20AMeV to 50AMeV a fraction exceeding 40% in projectile electron loss [8] to be attributed to multiple electron loss.

For this case the validity of the independent particle approximation using binominal statistics to derive multiple ionization from single ionization is not firmly established and will thus not be used, as this may conceal the intrinsic many-body nature of the interaction at the strong perturbation prevailing. At this time there is no a priori theory for complete differential cross sections on multiple electron emission in the strongly non-perturbing collision regime.

For this reason a meaningful experiment studying the contribution of the multiple ionization channel in electron loss for $U^{28+}$ projectiles needs to apply direct measurements of all respective channels as the momentum transfer is dependent on the multiplicity of emission and thus the partial DDCS and also the shape of the continuum distributions is expected to depend on the multiplicity.

One may consider the previous experiment measuring the single differential cross section $d\sigma/dp$ as proof of principle for the experimental procedure for multi-electron ionization of projectile:

\[ 90\text{AMeV } U^{88+}(1s^22s^2) + N_2 \rightarrow U^{89+}(1s^22s) + e_{\text{cusp}}(0^0) \text{ single ionization} \]

In the currently proposed experiment we will make use of the fact that in the ionization detectors detecting charge exchanged projectiles, which are positioned in the dipole following the jet target, 2 charge states of the charge exchanged beam may be distinguished. It is thus possible to measure inpendently the single and double electron loss channels:

\[ 20-50 \text{ AMeV } U^{28+} + [H_2, \text{He, N}_2, \text{Xe}] \rightarrow U^{30+} + (2) e_{\text{cusp}}(0^0) \text{ Double Ionization DI} \]
We have equipped the 2D position sensitive electron detector with a new hexagonal anode, which in principle allows to detect simultaneously two electrons transmitted from the target zone with the same momentum onto the detector as long as the location of the two hits is separated by more than 10 mm. However, at this time there is no theoretical prediction about the relative energy of two electrons in the continuum in double ionization in strong perturbation. True 2-electron spectroscopy in double ionization is limited at this time to strong field laser ionization [13].

III. Requested beam time

We propose to measure the double differential cross section for single and double electron loss from the $^{28+}$ projectile for H$_2$, He, N$_2$ and Xe targets for 20 AMeV and 50AMeV collisions energy in the ESR storage ring (50AMeV is the maximum energy for $^{28+}$ in the ESR). For benchmarks for ab initio symmetric eikonal theory we propose to also measure single ionization 90 AMeV $^{88+},^{90+}$ +Ar $\rightarrow$ $^{89+},^{91+}$ +e$^-$ to compare new experimental with existing theoretical double differential cross sections for 1s and 2s ionization in He and Be-like Uranium by Surzhykov and Voitkov, as given in figs. 9 and 10.

The beam time necessary is determined by the statistics to be accumulated for the double ionization for $^{28+}$; at this time DDCS for double ionization DI for $^{88+}$ is not considered, only single differential cross sections $d\sigma/dp$ are considered for electrons from DI.

The fraction of double ionization for electron loss in $^{28+}$ ranges from 40% of single ionization for high Z targets to less than 10% for H$_2$ [8]. The second critical factor is the number of points necessary for a single differential cross section $d\sigma/dp$ to derive a useful grid in ($p_{\parallel}$, $p_{\perp}$) for the double differential cross section. With a size of 64 by 64 bins as a marginally acceptable resolution for the data on the 2D position sensitive detector we find for $10^8$ projectile-ions, an areal target density of $10^{11}$ cm$^{-2}$, 10 data points over $d\sigma/dp$ and a minimum of 50 events per bin, the ESR revolution frequency 3 $10^5$, the fraction of the cross section within the acceptance of the forward spectrometer $p_{\text{fraction}}$, the ring duty cycle $e_{\text{ring}}$ and the fraction of the cross section covered in each data point along the momentum axis $s_{\text{scan}}$ using $N_{\text{e}} = n_i n_T d\sigma_{\text{loss}} f_{\text{esr}} p_{\text{fraction}} e_{\text{ring-dutycycle}} s_{\text{scan}}$ total electron rates form 2/sec to 800/sec, depending on the varying theoretical cross sections and technical parameters.

The lowest SI cross section occurs for H$_2$ and thus will be true for double ionization DI.

The longest data-taking is necessary for DI in $^{28+}$ + H$_2$ with 12h for 1s ionization (SI) for $^{90+}$ with 21h as here due to the much broader Compton profile for U 1s only a small fraction of electrons ionized into the continuum will appear in the ELC cusp. Electrons are spread much further in momentum space (similar to what is seen for REC width for different target Z).

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<th>For beam studies with 2 charge states</th>
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<td>For $^{88+},^{90+}$ projectiles</td>
<td>In total we request 179 hours = 23 shifts</td>
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36. It is interesting to note that most advanced theories for inner shell ionization may well predict the impact parameter dependence[29-32] (i.e. momentum transfer dependence) of e.g. K- vacancy creation, but fail to account for the
details of the impact parameter dependence of the primordial electrons and the corresponding energy and angular distribution [20, 21, ...].

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38. In spite of its apparent significance, quantitative comparisons of experiments and theory for ionization related electron continua have been only satisfactory in the description of the simplest total and some partial or differential ionization cross sections which integrate over energy and/or emission direction of the ionized electron [26-29]. The crucial and decisive details of the electron emission with respect to angular and energy distribution in their dependence on the very diverse collisions dynamics (consider e.g. the time-dependent electromagnetic fields during intense photon and highly charged ions induced ionization) and certainly all differential cross sections for multiple electron emission for strong field/strong perturbation stubbornly evade a quantitative description to date [13, 15, 16, 17......................].