IOP Publishing Journal of Physics: Conference Series **58** (2007) 307–310
doi:10.1088/1742-6596/58/1/068 13th International Conference on the Physics of Highly Charged Ions

Radiative Electron Capture to Continuum (RECC) in 90AMeV $U^{88+}(1s^2 2s^2) + N_2$: the Short Wavelength Limit of Electron Nucleus Bremsstrahlung

M Nofal[1,3], S Hagmann[2,3], Th Stöhlker[3], D H Jakubassa-Amundsen[4], Ch Kozhuharov[3], X Wang[5], A Gumberidze[3], U Spillmann[3], R Reuschl[3], S Hess[3], STrotsenko[3], D Banas[3], F Bosch[3], D Liesen[3], R Moshammer[1], J Ullrich[1], R Dörner[2], M Steck[3], F Nolden[3], P Beller[3], K Beckert[3] and B Franczak[3]

[1]Max Planck Inst. f. Kernphysik, Heidelberg,
[2]Institut f. Kernphysik, Univ. Frankfurt,
[3]GSI-Darmstadt,
[4]Mathematisches Institut, LMU, München,
[5]Fudan University, Shanghai

E-mail: s.hagmann@gsi.de

Abstract. We have investigated the relation of forward emission cusp electron spectra and bremsstrahlung for 90AMeV $U^{88+} + N_2$ at the internal supersonic gas jet target of the ESR storage ring of GSI. We find that x ray photons measured in coincidence with cusp electrons originate from the short wavelength limit of the electron nucleus bremsstrahlung.

1. Introduction

The fundamental process of electron-nucleus bremsstrahlung is a consequence of the general coupling of electromagnetic and matter fields. Classically radiation is emitted in every collision for which the momentum transfer $q \neq 0$ and thus the acceleration $\mathbf{a} \neq 0$. Incident and scattered electron and photon lie in one plane. The radiation is emitted perpendicularly with respect to the acceleration vector **a** and the spectrum falls to zero at $\omega\tau \approx 1$, where ω is the photon energy and τ the collision time. Quantum mechanically the kinematic relations still hold, but the probability of radiation is $p \sim \alpha$ due to the coupling of electromagnetic and matter fields mediated by the fine structure constant α. A notable digression from the classical features of the bremsstrahlung spectrum is that the differential cross section exhibits a finite value at the short wavelength limit/1/. Kinematically complete experiments as the most sensitive tests of theoretical calculations of the fundamental process of electron nucleus bremsstrahlung have been pioneered by the Tübingen group of Nakel/1/. Here electrons impinge on a very thin solid target foil, emerging scattered electrons are measured in coincidence with the emitted bremsstrahlung photon, where for both energy and emission direction is determined. These kinematically complete experiments can only be performed in the long-and medium wavelength range of x-rays and never in the short wavelength limit: in the bremsstrahlung process at the short wavelength limit the incident electron gives up its entire kinetic energy to the emitted photon and –

with $E_{kin} \approx 0$ - cannot leave the target foil. The short wavelength limit of the electron nucleus bremsstrahlung is, however, of utmost theoretical interest due to its deep lying relation with the fundamental process of photoionization/2,3/. For this reason total differential cross sections extending up to the short wavelength limit are of considerable interest. We now have shown that an investigation of electron nucleus bremsstrahlung and forward electrons emitted in heavy ion-atom collisions offers access to total differential cross sections at the short wavelength limit. In inverse kinematics a target electron in an inelastic collision with a projectile ion can emit bremsstrahlung with laboratory energy up to the short wavelength limit $E_x^{lab} = \frac{(\gamma-1)mc^2}{\gamma(1-\beta\cos\theta^{lab})}$, where β and γ correspond to the velocity of the incident projectile ion. The electrons corresponding to photons with E_x^{lab} have an energy $\varepsilon \approx 0$ in the projectile frame, in the laboratory frame the electrons appear with $E_{lab}=(\gamma-1)mc^2$, i.e. with projectile velocity in a narrow cone around the projectile direction. When in such a configuration, the primordial vector momentum of the electron can be measured in coincidence with the bremsstrahlung photon it becomes possible to determine the fourfold differential cross section $\frac{d^4\sigma}{d\Omega_x d\Omega_e dE_x dE_e}$ at the short wavelength limit. We have implemented into the ESR an imaging forward electron spectrometer which – when operated simultaneously with a reaction microscope – will permit to conduct such measurements. As a first step, we have measured coincidences between bremsstrahlung photons and electrons emitted into the forward cone and thus have determined single differential cross sections for the radiative electron capture to continuum cusp.

2. Experimental Procedure

The experiment was performed at the internal supersonic gas target of the ESR storage ring of GSI. U^{65+} ions from the SIS synchrotron with a specific energy of 90AMeV are post stripped using a thin C foil and U-ions selected in charge state 88+ were then injected into the ESR.

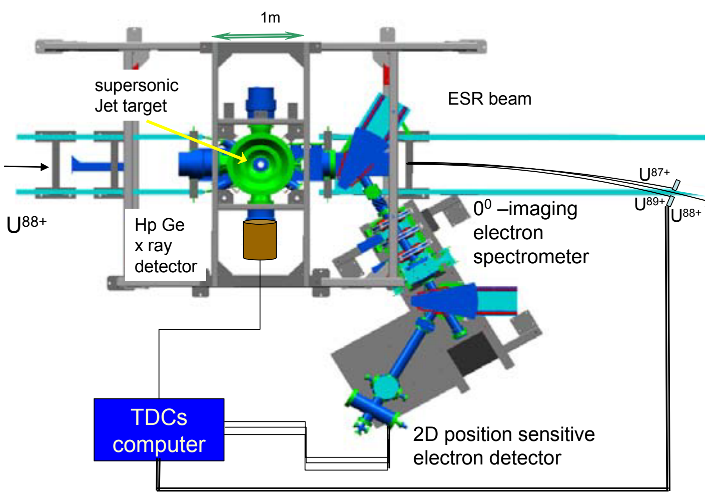

Figure 1. Setup of the electron spectrometer at the supersonic internal target area of ESR. X rays are detected at 90^0, charge exchanged projectiles in the first dipole magnet following the target and electrons are momentum analyzed with the forward electron spectrometer. The data acquisition permits coincidences between any two of the reaction products

Beam components undergoing charge exchange during electron cooling are intercepted by scrapers in the dipole magnet following the cooling section so that only the U^{88+} beam traverses the N_2 gas target, which has an areal density $\approx 10^{12}/cm^2$. Projectiles in charge state U^{87+} and U^{89+}, which have undergone a charge changing collision in the target zone, are detected with multiwire proportional counters MWPC after the first dipole magnet following the target zone. X rays from the target zone are detected at 90^0 with respect to the beam axis with a 2000 mm^2 HpGe x ray detector. Electrons emitted in the forward direction at $0^0 \pm 1.9^0$ are separated from the coasting beam by a first 60^0dipole magnet downstream of the target zone. This magnet is the first optical element of the imaging forward electron spectrometer, consisting of a 60^0 dipole, a quadrupole triplet and a second 60^0 dipole. Following momentum defining slits, electrons are detected with a channelplate detector equipped with a 2D position sensitive delay line anode.

The control of the electron spectrometer is integrated into the ESR control software, which steps the B-fields of the spectrometer's optical elements and also sets the correction coils implemented into the ring lattice to compensate for the small deflection effected on the coasting beam by the first 60^0 magnet of the electron spectrometer. Relative double differential cross sections for forward electron production are measured by incrementing the electron spectrometer's B-fields after a predetermined number of fillings of the ESR from SIS. The time correlation of electrons measured in coincidence with x rays at 90^0 and with charge changed projectiles U^{87+} and U^{89+} was registered in event-by event using standard NIM and CAMAC fast-slow coincidence technique and the GSI MBS system/6/.

3. Results and Discussion

In collisions of non-bare heavy projectiles with light targets the projectile centred electron continua play a key role. They are attributed to projectile electron loss to the continuum and to radiative and non radiative capture processes into the projectile continuum/5/. In the following, we will briefly present some preliminary results on these channels and their relationship to the bremsstrahlung continuum. Coincidences between the cusp electrons with $\vec{v}_{electron} \cong \vec{v}_{projectile}$ and the charge exchanged projectiles U^{89+} (see figure 2) revealed that a large fraction of the forward electron emission can be contributed to the electron loss cusp (ELC) from 90 AMeV Be-like U^{88+} + N_2 ==> U^{89+} + $\{N_2^{i+*}\}$ + e .

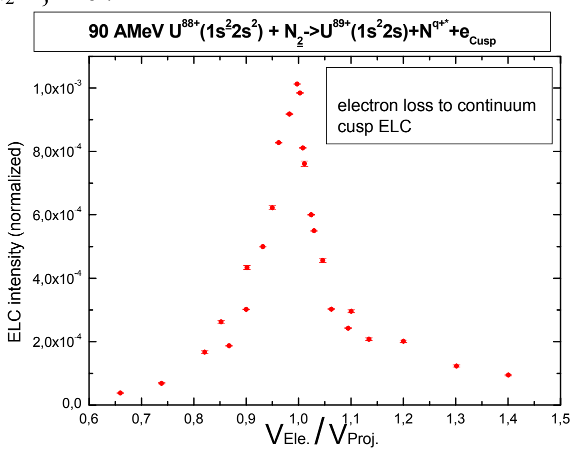

Figure 2. Electron loss to continuum cusp(ELC) cusp measured for 90 AMeV Be-like U^{88+} +N_2. Electrons emitted close to 0^0 with respect to the beam direction and momentum analyzed are detected in coincidence with charge exchanged Li- like projectiles U^{89+}.

Preliminary calculations by A. Surzhykov indicate that the dominant contribution to the ELC cusp originates from 2s electrons in the U^{88+} projectile/4/. A detailed analysis of the cusp shape is in progress. At a rate lower than that for the electron coincidences with the Li like U^{89+}, we find electrons coincident with B-like U^{87+} ($1s^2 2s^2 2p$) which originate from a simultaneous capture of one target electron into a bound state and one into a near continuum threshold state of the projectile (see figure 3).

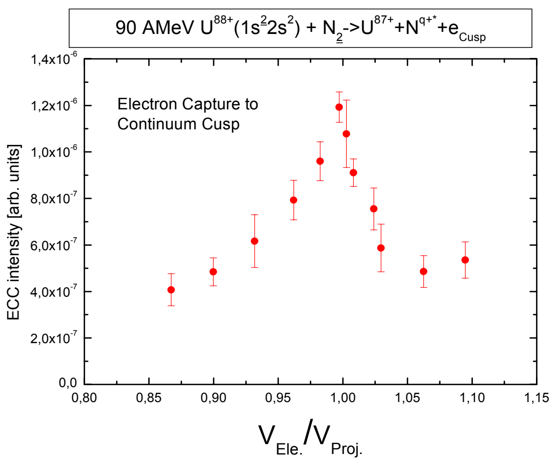

Figure 3. Correlated electron capture to continuum cusp (ECC) for simultaneous capture to a bound and a continuum state near threshold in the projectile for 90AMeV U^{88+}+ N_2==> U^{87+} + $\{N_2^{i+*}\}$ + e .

The cusp centred at $v_e \approx v_{proj}$ is visibly skewed to the low energy side. This precludes the interpretation of its origin as a double capture to bound states with subsequent autoionization as this would result in a cusp symmetric in shape on the high and low side of the cusp. There is at present no theoretical approach to describe this correlated simultaneous capture at relativistic velocities and further experiments on the velocity dependence and the target Z dependence are in progress.

In figure 4 we compare the x ray spectra coincident with electrons around $v_e \approx v_{proj}$. In the coincident x ray spectra we observe that virtually all coincidences are associated with x ray photons from the short wavelength limit of the electron-nucleus bremsstrahlung. Electrons with velocity slightly below the projectile velocity produce significantly fewer coincidences than electrons with a laboratory velocity slightly larger than v_{proj}. This can be interpreted as electrons having lost their entire kinetic energy in the Bremsstrahlung process and being bounced back from the projectile (seen in the projectile frame) into the forward direction (seen in the laboratory frame). A detailed analysis and a comparison with the asymmetry predicted by a relativistic impulse approximation is in progress.

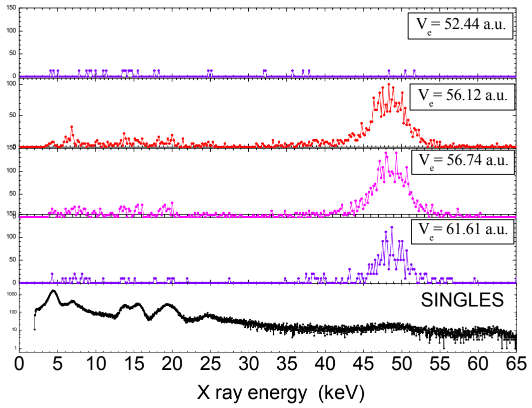

Figure 4. x ray spectra measured in coincidence with electrons emitted in the forward direction and momentum analyzed with the forward electron spectrometer. It is clearly seen that only coincidences with x rays from the short wavelength limit of the electron-nucleus bremsstrahlung appear; it is very apparent that mostly electrons with projectile frame momenta parallel to the incident projectile are generating coincidence events.

4. Summary

We have developed a new experimental method for unambiguous coincident detection of the bremsstrahlung photons from the short wavelength limit. In a first demonstration we have measured coincidences between electrons from the RECC cusp and bremsstrahlung at 90^0 for 90AMeV U^{88+} + N_2 collisions and shown that RECC-cusp electrons originate from the fundamental process of electron nucleus bremsstrahlung at the short wavelength limit. A comparison on an absolute scale is deferred to future work. We note that with a configuration where, besides a 2D position sensitive detector for cusp electrons, all pertinent momenta are determined – e.g. using a reaction microscope – the measurement of fully differential cross sections for the short-wavelength limit of electron-nucleus bremsstrahlung becomes possible for the first time.

References

[1] Haug E and Nakel W 2004 ‘The Elementary Process of Bremsstrahlung’ *World Scientific Lecture Notes* **73**
[2] Fano U *et al* 1958 *Phys. Rev.* **112** 1679
[3] Pratt R *et al* 1960 *Phys. Rev* **120** 1717 ; Pratt R *et al* 1975 *Phys. Rev.* A **11** 1797
[4] Surzhykov A 2006 private communication
[5] Shakeshaft R and Spruch L 1979 Rev. Mod. Phys. **51** 369
[6] Kurz N *et al* http://www-w2k.gsi.de/daq/