X-Ray Emission from High-Z Projectiles Colliding with Gaseous Matter

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K-Shell Projectile Excitation Studied for High-Z Ions

Besides electron capture processes, Coulomb excitation is the most important production process of characteristic projectile photons in swift encounters of high-Z ions with target atoms. In contrast to electron capture processes which were studied in great detail at relativistic collision conditions, no experimental data for collisionally induced projectile excitation are available for high-Z ions. This process is almost equivalent to projectile ionization, except that the active electron is excited into a bound state and not into a continuum state of the projectile. The latter, has been studied for high-Z ions in various experiments involving beam energies between 100 MeV/u and 1 GeV/u where the effects caused by the magnetic part of the Lienard-Wiechert interaction were of particular interest [1]. However, within the overall uncertainties of the available data, the K-shell ionization cross-sections turned out to be rather insensitive to these effects. The formation of excited states via Coulomb excitation can be studied uniquely for one- and two-electron high-Z ions by the observation of the radiative decay of the excited levels to the ground state. Owing to the large fine structure splitting in such heavy ions, the cross sections for ground state excitation into the various L-shell sublevels can unambiguously be determined. This means that in contrast to K-shell ionization, both the initial and the final state of the electron undergoing Coulomb excitation are controlled experimentally [2]. In the following, we concentrate on the role of the magnetic interaction for the excitation/ionization process in relativistic ion-atom collisions. As an example the reduced cross-sections (σ/Z^2_T) for excitation into the $2p_{3/2}$ level are shown in figure 1, calculated for the case of H-like Bi^{82+} at 119 MeV/u (full line: inclusion of the complete Lienard-Wiechert interaction; dotted line: only the electric part of the electron-target interaction is considered) [3]. Here, Z_T denotes the nuclear charge of the target. Surprisingly, the consideration of the magnetic part of the interaction leads to a strong reduction (by almost 30%) of the absolute cross-section values pointing to an interference between the amplitudes for the electric and magnetic part of the interaction. In fact, these theoretical findings seem to be confirmed by the data obtained in an experiment conducted at the Fragment Separator (FRS) (see open circles given in the figure). Note, that such a destructive interference between the electric and the magnetic part of the interaction points to a break-down of the dipole-approximation. By considering the dipole approximation only, an approach commonly used for high-Z ions, the magnetic (transverse) part of the interaction must always lead to a cross-section enhancement [4]. During the last beam time performed at the ESR, we extended these investigations by studying excitation of He-like uranium in collisions with gaseous targets, where for the first time, also heavy targets such as Kr and Xe were used. The main interest focuses on the study of the $K\alpha_2$, $K\alpha_1$ x-ray production yields,which essentially reflect the excitation cross - ections to the $[1s_{1/2},2p_{1/2}]^3P_1$ and $[1s_{1/2},2p_{3/2}]^1P_1$ states. Note, that excitation to the $^3P_1$ state is a pure relativistic effect and does not occur for low-Z projectiles. For high-Z systems, however, the excitation to the $^3P_1$ state is found experimentally to be almost as strong as the excitation to the $^1P_1$ level (see upper part in figure 2).

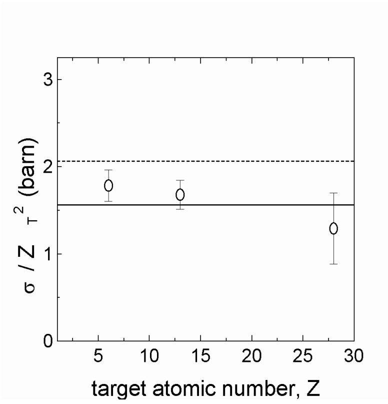

Figure 1: *Reduced cross sections for excitation into the $2p_{3/2}$ level, calculated for the case of H-like Bi^{82+} at 119 MeV/u. (solid line: inclusion of the magnetic interaction; dashed line: only electric interaction). The open circles refer to experimental results.*

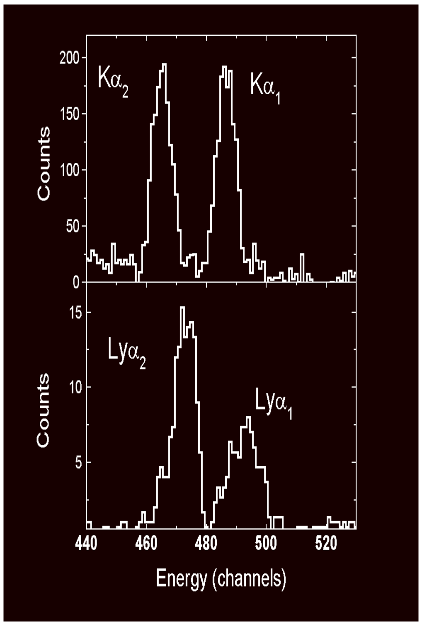

Figure 2: *X-ray spectra recorded for He-like U^{90+} at 223 MeV/u colliding with a Kr gasjet target. In the upper part the spectrum associated with ground-state excitation is shown. The spectrum in the lower part was measured in coincidence with electron loss (random contributions are not subtracted).*

The data collected at the ESR gasjet target are presently under evaluation. We would like to emphasize the uniquely clean conditions of the ESR gasjet target for such investigations. Here, solid-state effects (e.g. multiple collisions) are completely absent and allow one to study higher order effects, such as excitation and ionization occurring in one collision (see lower part in the figure). Since He-like ions are the simplest multi-electron systems, the investigation of such processes in the high-

Z regime may provide detailed insight into the role of electron-correlation effects in strong central fields.

X-Ray Emission and Charge Exchange Cross-Sections of Decelerated Uranium Ions

The successful planing of experiments dealing with high-Z decelerated ions requires a precise estimation of beam losses caused by charge exchange processes between the stored ions and the residual gas atoms (molecules). In particular, when the ESR gasjet is needed, the large charge exchange cross-sections at low energies may drastically reduce the lifetime of the stored ion beam. Note, that in contrast to the high energy regime, up to now no experimental cross-section data are available for bare or even few-electron, high-Z ions colliding with atoms far below the production energy of the high projectile charge-states.

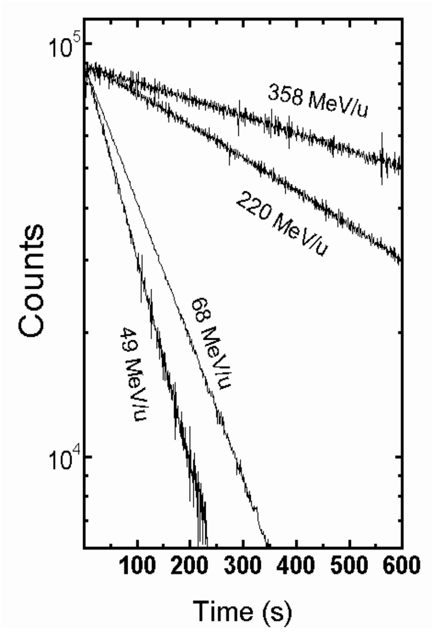

Figure 3: *Charge exchange rates measured at the ESR gasjet target for bare uranium ions colliding with N_2 molecules.*

In the following we consider only beam losses in the ring which are caused by charge exchange in the gasjet target. For our charge exchange studies of the decelerated bare uranium beam, a N_2 gasjet target with an areal density of $0.5 \times 10^{+12}$ particles/cm^2 was applied and the beam lifetimes were determined from the charge exchange rates measured by the particle detector for the down-charged U^{91+} ions. In figure 3 the corresponding count rate spectra obtained at the various beam energies, normalized to one common scale, are given as a function of time. As shown in the figure, the deceleration of the ion beam to energies as low as 49 MeV/u leads to a drastic reduction in lifetime down to about 1 min which has to be compared with the lifetime of about 20 min measured at the high energy of 358 MeV/u. This is a consequence of the strongly enhanced electron pickup cross sections at low beam energies, where *Non-Radiative Electron Capture* (NRC) is by far the most important charge exchange process. In order to obtain precise cross-section data, the total charge exchange rates were normalized to the measured K-REC x-ray intensities as the latter process has been studied in great detail by experiment and theory. In figure 4, the resulting cross-section data (solid circles) are compared with a theoretical calculation (full line) based on the relativistic eikonal approximation for NRC (dashed line) [1]. In addition, the calculation takes into account the competing Radiative Electron Capture (REC) using the dipole approximation which treats REC as the time reversed photo ionization process. As seen in the figure, an excellent agreement between the experimental results and the theoretical predictions can be stated. We believe, that this agreement, in particular at low energies, is fortuitous, since the eikonal approximation is known to give absolute cross-section values only within a factor of two. However, the results provide valuable information for future experiments dealing with decelerated high-Z ions.

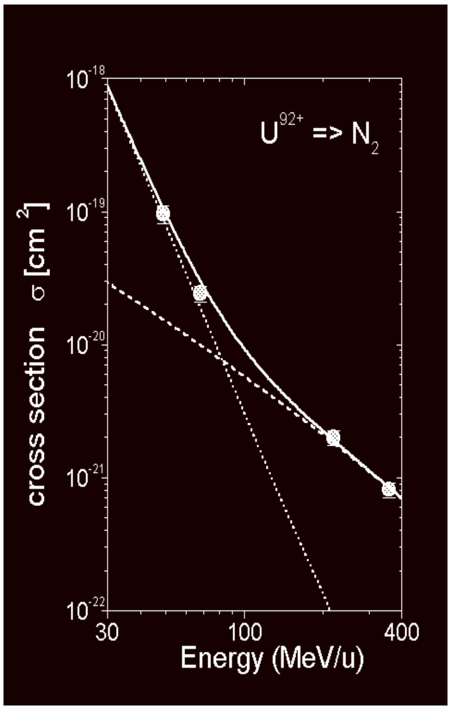

Figure 4: *Charge exchange cross sect-ions measured for U^{92+} (N_2 collisions at the ESR storage ring (solid circles). In addition the data are compared with theoretical calculations (full line). For details see text.*

Balmer Transitions of Hydrogen-Like Uranium

In contrast to total charge exchange cross-section data, the characteristic x-ray radiation produced by electron capture into bare projectiles allows us to measure exclusive population cross-sections which provide a stringent test of electron-capture theories. However, until now, such data were not available for high-Z ions. As has been reported recently, the projectile x-ray emission associated with electron capture into decelerated, bare uranium ions deliver an abundant yield of characteristic x-ray transitions. In particular, strong Balmer and even Paschen transitions show up which provide a unique means for a test of electron capture theories dealing with NRC. Here, due to the large fine structure splitting in high-Z ions, *n,l,j*-sensitive population cross-sections can be obtained. This is depicted in figure 5, where the Balmer spectrum of H-like uranium is shown. This was recorded for initially bare uranium ions colliding with a N_2 gasjet target at an energy of 68 MeV/u. The full line in the figure represents the result of a spectrum simulation. The latter is based on the post-version of the eikonal approximation. For completeness, the REC process was also taken into account. Moreover, all projectile shells up to *n=40* were considered in order to describe the high energy part of the spectra where transitions from Rydberg levels are located. We emphasize, that the appearance of such Ryberg transitions is a unique feature of the gasjet target since in solid target experiments high-n levels are almost completely depopulated in subsequent collisions. As can be seen in the figure, the applied theoretical approach is in excellent agreement with the experimental spectra. However, the Oppenheimer-Brinkman-Kramers (OBK) approximation, which is commonly used in order to predict the *n,l*-distribution of NRC, is in strong variance with the post-version of the eikonal approach and consequently fails completely in describing the measured x-ray spectra. This is shown in the upper part of figure 3 where the eikonal-approach (full line) is compared with OBK calculations (dotted curve). Therefore, we conclude that such detailed information, like the final *n,l* distribution, cannot be derived from the OBK approximation in a proper way.

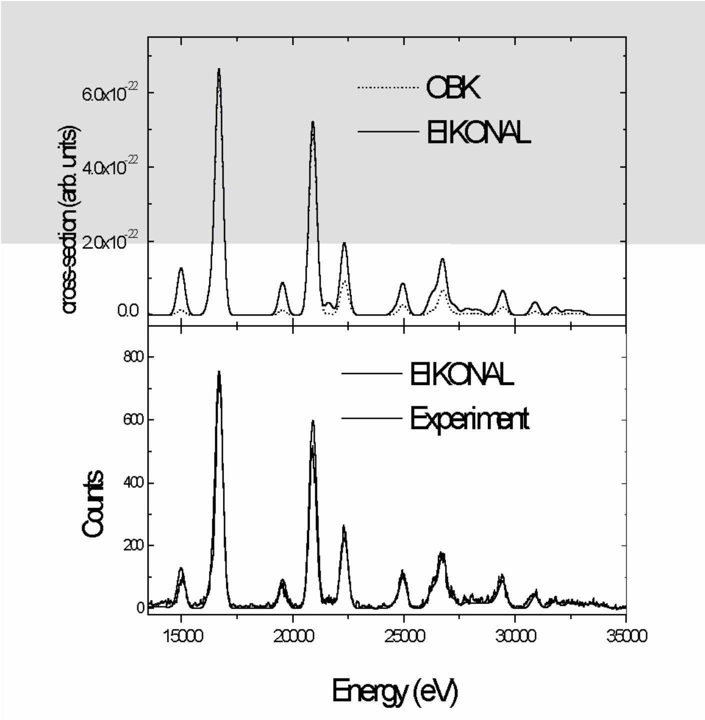

Figure 5: *Balmer spectrum of H-like uranium (lower part) measured for initially bare uranium ions colliding with a N_2 gasjet target at an energy of 68 MeV/u (full line: simulation based on the eikonal approximation). In the upper part spectrum simulations based on the eikonal approximation (full line) [6] and the OBK approximation (doted line) are compared.*

Strong Alignment Observed for the Time-Reversed Two-Step Photoionisation Process

As has been discussed very recently [5,6], the photo effect in the relativistic domain can be investigated uniquely by the study of its time-reversed analog in relativistic ion-atom collisions, i.e. the study of the *Radiative Electron Capture* process.

In the following, we consider the inverse of a two-photon/one-electron ionization process. Here, the first photon resonantly excites an electron from the $1s_{1/2}$ ground state into the $2p_{3/2}$ hydrogenic state and subsequently the second photon ionizes the excited electron within the lifetime of the $2p_{3/2}$ state, i.e. for the case of H-like uranium a time of the order of 10^{-17} s. We are interested in the magnetic subshell population of REC into the $2p_{3/2}$ state. Such information elucidates in detail the dynamics of the elementary photo ionization process [6] in the domain of high-Z one-electron ions where the electron-photon interaction is governed by relativistic effects. Usually, information about degenerate atomic states, which differ only in their magnetic quantum number, is obtained by polarization measurements. However, since for high-Z ions, like uranium, the Ly-α_1 transition energy appears close to 100 keV, a polarization measurement is almost impossible. Here, the alignment of the $2p_{3/2}$ state and consequently its magnetic-substate population can be deduced only from an angular distribution measurement. The experiment was performed with bare Pb^{82+} and U^{92+} projectiles at the gasjet target of the ESR storage ring. The experimental setup is described elsewhere [5]. In order to reduce possible systematic uncertainties, the angular distribution of the intensity of the investigated Ly-α_1 transition ($2p_{3/2} \rightarrow 1s_{1/2}$) was normalized to the Ly-α_2 radiation ($2s_{1/2}$,$2p_{1/2} \rightarrow 1s_{1/2}$) which is isotropic in the emitter frame. Moreover, in order to control possible cascade population of the $2p_{3/2}$ state, also the Balmer spectra were recorded (see figure 6). All prominent lines in the cascade spectra were identified as originating from j=1/2 states (see transition assignment given in the figure). Therefore no alignment is introduced by cascades.

Figure 6: *Upper part: Balmer spectrum observed in coincidence with electron capture for U^{92+}(N_2 collisions at 358 MeV/u). Bottom part: simplified level scheme of high-Z H-like ions. For the state with n>2 only the j=1/2 levels are considered which may feed the $2p_{3/2}$ state via cascades.*

(The full line given in Fig. 6 refers to a spectrum simulation based on fully relativistic REC cross-section calculations). From the measured alignment of the $2p_{3/2}$-levels of H-like Pb^{81+} and U^{91+} follows that about 75% of the capture events populate the $\mu = \pm 1/2$ sublevels of the $2p_{3/2}$ state which corresponds to a 40% linear polarization of the emitted Ly-α_1 radiation. Moreover, subtracting the cascade contribution, we can deduce that direct radiative capture into the $2p_{3/2}$ state populates the $\mu = \pm 1/2$ magnetic sublevels by more than 90%. This means that this particular process leads to an emission of Ly-α_1 photons which are strongly polarized by as much as 50%. We have to emphasize, that to our knowledge, no other non-resonant process in which such a strong alignment occurs has been identified in fast ion-atom/electron-ion collisions.

[1] For a summary of relativistic atomic collisions, see e.g. J.Eichler,and W.E. Meyerhof, *Relativistic Atomic Collisions* (Academic Press, San Diego, 1995)

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