Excitation of High-Z One- and Two-Electron Ions in Relativistic Collisions with Gaseous Targets

T. Ludziejewski [a,e] Th. Stöhlker [a] H. Beyer [a] F. Bosch [a] S. Fritzsche [c] D. C. Ionescu [d] C. Kozhuharov [a] A. Krämer [a] D. Liesen [a] P. Mokler [a] P. Rymuza [e] Z. Stachura [f] P.Świat [g] A. Warczak [g]

[a] *Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany*

[b] *University of Frankfurt, Germany*

[c] *University of Kassel, Kassel, Germany*

[d] *Lawrence Berkeley National Laboratory, Berkeley, USA*

[e] *Soltan Institute for Nuclear Studies, Swierk, Poland*

[f] *Institute of Nuclear Physics, Cracow, Poland*

[g] *Institute of Physics, Jagiellonian University, Cracow, Poland*

Abstract

Progress in the studies of ground state excitation of heavy hydrogen-like and helium-like ions in relativistic collisions with atoms is reported. In particular the recent results obtained in experiments carried out at the internal gas-jet target of the ESR Storage Ring at GSI-Darmstadt are presented. Special emphasis is given to the sensitivity of the measured state selective cross sections to the magnetic effects occurring in relativistic heavy-ion–atom collisions.

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Corresponding author: Tomasz Ludziejewski
Gesellschaft für Schwerionenforschung
Planckstraße 1
D-64291 Darmstadt
GERMANY
Telephone: +49 6159 71-2796, Facsimile: +49 6159 71-2901
Email: T.Ludziejewski@gsi.de

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1 Introduction

Electron excitation in relativistic collisions with atoms at velocities $\beta = v_{proj}/c < 1$ offers the special opportunity to study the relatively weak, as compared to the electric, magnetic part of the Liénard-Wiechert interaction potential. In particular, for this energy regime, the ground state electron excitation seems to be sensitive to a (destructive) interference between electric and magnetic amplitudes of the complete interaction potential. Such effects are difficult to access experimentally in the electron loss experiments, where the infinite number of final (continuum) electron states contribute to the total ionization amplitude. Recently, the first study of the K-shell electron excitation in collisions of H-like and He-like Bi ions with solid matter at relativistic velocities has been reported [1]. In that work, a new treatment based on the complete relativistic formalism has been applied for the first time to calculate cross sections for excitation into the individual magnetic sub-states of the excited Bi^{82+} levels. Within this approach, the transition amplitude is derived in the framework of the first order perturbation theory, and has the form (see Refs. [1,2] for further details):

$$A^{\mathrm{e}}_{fi}(b) = \mathrm{i}\frac{\gamma Z_{\mathrm{P}} e^2}{\hbar} \int \mathrm{d}t\, \mathrm{e}^{i(E_f - E_i)t/\hbar} \times \int \mathrm{d}^3 r\, \varphi_f^\dagger(\vec{r})(1 - \beta\alpha_z)\frac{1}{r'}\,\varphi_i(\vec{r}). \tag{1}$$

For the description of initial φ_i and final $\varphi_f^\dagger$ electron states the Coulomb-Dirac wave-function were used. In Eq. (1) the term proportional to α_z corresponds to the magnetic part of Liénard-Wiechert potential. It is worthwhile to note that within this picture the electric and magnetic contributions to the total transition amplitude are added up coherently.

Figure 1 shows the theoretical cross sections for excitation into the H-like Bi L-shell levels with total angular momentum states $j = \frac{1}{2}$ and $j = \frac{3}{2}$ at incident energy 119 MeV/u, along with the experimental data [1]. In addition to the complete calculations (solid line), results are plotted where solely electric part of the interaction potential is considered (dashed line). Comparison of the two calculations demonstrate, that the inclusion of the magnetic term leads to a significant (almost 30%) *reduction* of the absolute cross section values, pointing to the presence of a destructive interference effects. The experimental data depicted in the figure favor the "complete" calculations. These first results indicated the importance of a complete relativistic treatment of the exciatation process, however the experimental data suffered from the relatively poor counting statistics, and uncertainties associated with the solid targets used.

Here we report on the experiments performed at the ESR storage ring at GSI-

Darmstadt, aimed at a precise determination of the Coulomb excitation cross sections for the ground state electrons. The combination of the excellent quality relativistic ions beams and the internal gas-jet targets, routinely available at the ESR storage ring, guaranteed very clean experimental conditions for the studies of the electron excitation of the relativistic high-Z projectiles. In the experiment, the Kα and Kβ series radiation of the 223 MeV/u He-like uranium and the 256 MeV/u H-like gold ions, produced in collisions with light (CH_4, N_2, and Ar) gas targets were observed. For the first time at the ESR storage ring, also the heavy (Kr, and Xe) targets were used. A novel technique applied for the cross section determination [4], based on relative normalization to the more precisely known cross sections for radiative electron capture (REC), ensured an accuracy typically better than 10%.

2 Experiments

The experiments were performed at the SIS-ESR (heavy-ion synchrotron – experimental storage ring) facility at GSI in Darmstadt. The beams of U^{90+} and Au^{78+} ions delivered by the SIS accelerator were accumulated and cooled in the ESR storage ring. The final beam energies were 223 MeV/u, and 256 MeV/u for the U^{90+} and Au^{78+} ions, respectively. The experimental setup used in the measurement with uranium ions was described in details elsewhere [3]. Essentially the same apparatus was used in the measurements with the H-like Au beam. In this case, x-rays from the beam – gas-jet target interaction zone were registered by three Ge(i) detectors placed at observation angles equal to 35°, 90°, and 150° with respect to the beam direction. Molecular CH_4, N_2, and atomic Ar gas targets with typical areal densities $\sim 10^{12}$ particles/cm^2 were used. The x-rays were measured in coincidence with projectiles which changed their charge state (Au^{77+} corresponding to the electron capture to the projectile, and Au^{79+} corresponding to the electron loss). Simultaneously, the "single" (no coincidence condition) spectra were recorded.

3 Results

3.1 He-like systems

Figure 2 shows sample x-ray spectra for He-like U incident upon the N_2, Ar, Kr, and Xe gaseous targets measured at observation angle equal to 132°. In all cases the prominent and well resolved Kα_1, Kα_2 and Kβ transitions could be seen. Since the spectra were measured with gaseous targets guaranteeing single collision conditions, the measured photon yields directly correspond to the x-ray production cross sections due to the ground state electron excitation.

In Fig. 3 the total cross sections are plotted versus target nuclear charge (Z_T). The absolute cross section values were obtained by normalizing the simultaneously measured L-REC photons on rigorously calculated relativistic cross sections [2] (see also Ref. [4] for the detailed discussion of the applied normalization method). For the N_2, Ar, and Kr targets the total cross sections follow approximately the Z_T^2 scaling law, characteristic for the first order perturbation theory. However, this proportionality seems to break down for for heaviest (Xe) target pointing to the inadequacy of the first order perturbative methods for exceedingly high Z_T.

As it has been already pointed out in Ref.[1], for He-like systems the rigorous comparison of the experimental data with theory requires calculations in which the realistic (self-consistent) electron wave-functions, and the correct angular momentum coupling scheme are considered. The extension of the existing code for multi-electron systems is presently being developed [5]. However, we would like to emphasize the advantage of the applied experimental technique i.e. the use of low density gas-targets, and the high luminosity cooled ion beams, for studies of electron excitation process. First, the statistical significance of the data has been improved by more than an order of magnitude, with respect to the first experimental investigations [1]. Second, the systematic uncertainties associated with the production of the primary and secondary bremsstrahlung, as well as the contribution of the double-step processes, are nearly excluded in the case of experiments at the internal gas-jet target of the ESR storage ring. Therefore, we expect that the accuracy of the new data for U^{90+} will allow to critically investigate the role of magnetic interaction in relativistic collisions of He-like ions with matter. Moreover, since the measurements were performed for a wide range of the target nuclear charges, the applicability criteria of the first order perturbation theory can be verified experimentally.

3.2 H-like systems

While for He-like systems the observation of x-ray transition to the ground state of the projectile (under single collision conditions) is a direct signature of ground state electron excitation, for H-like systems the additional mechanism of the projectile x-rays should be considered. That is the radiative (REC) and non-radiative (NRC) electron capture which may directly, or through cascade feeding, lead to the emission of the projectile K x-rays. These charge changing processes can be however, discriminated experimentally if the x-rays are measured in coincidence with down-charged projectiles. Figure 4 shows sample spectra measured at observation angle 35° for the 256 MeV/u H-like gold bombarding the Ar gas target. The upper plot represent spectrum taken without coincidence condition, where x-rays from both the H-like (excitation) and the He-like (capture) Au ions can be seen. The middle plot represents spectrum taken in coincidence with gold ions which captured one electron. The lower plot shows spectrum obtained as a difference between the single and coincidence spectrum, and thus representing x-rays due to the ground state excitation process. As can be seen in the figure this “anti-coincidence” technique allows to efficiently discriminate the transitions in the H-like system, providing the direct information about the population yields of projectile levels by the excitation process. Here, not only excitation into the $j = \frac{1}{2}$ $(2s_{1/2} + 2p_{1/2})$ and $j = \frac{3}{2}$ $(2p_{3/2})$ states of the L-shell are readily apparent, but also transitions into the states with principal quantum numbers essentially up to the series limit can be observed. Furthermore, adopting the cross section normalization method based on the simultaneously measured (in the coincidence channel) K-REC emission, an unprecedented accuracy of the order of few percents can be achieved for excitation into the $j = \frac{1}{2}$ and $j = \frac{3}{2}$ states of the projectile L-shell. As exemplified in the case of Bi ions [1] such a precise cross section data will constitute a sensitive test of the role of magnetic interaction in relativistic ion-atom collisions. Moreover, since the influence of magnetic effects is different for monopole and dipole excitation modes responsible for the population of the projectile s and p states, also the relative cross section ratios provide an evidence for the importance of the magnetic effects. Here, the uncertainties associated with the absolute cross section determination are almost excluded. For example, the experimental cross section ratio $\sigma^{\text{exc}}(j = \frac{1}{2})/\sigma^{\text{exc}}(j = \frac{3}{2})$ (determined from the preliminary data analysis) for 256 MeV/u Au $\rightarrow$ Ar system is equal to 1.03±0.05. The calculations in which only electric part of the Liénard-Wiechert potential is considered yield the value $\sigma^{\text{exc}}(j = \frac{1}{2})/\sigma^{\text{exc}}(j = \frac{3}{2}) = 0.87$. The complete calculations in which magnetic interaction is considered, yield the value 0.97, thus bringing the experimental data and the theoretical values in good agreement.

4 Summary

The two examples outlined above demonstrate the potential of the high luminosity relativistic ion beams of the ESR storage ring and the internal gas-jet targets for the studies of the ground state electron excitation in relativistic ion-atom collisions. The combination of this technique with the novel method of the absolute cross section normalization, allows us to determine the total and angular momentum selective cross sections for electron excitation with accuracy better than 10%. For H-like systems the additional advantage of the method consists in the ability to clearly discriminate the x-rays associated with capture and excitation process. The presented new data provide more precise information for state selective excitation cross sections, where both the absolute magnitude, and the cross section ratios will allow to examine in details the role of magnetic interaction in relativistic ion-atom collisions.

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References

[1] Th. Stöhlker, D.C. Ionescu, P. Rymuza, F. Bosch, H. Geissel, C. Kozhuharov, T. Ludziejewski, P.H. Mokler, C. Scheidenberger, Z. Stachura, A. Warczak, R.W. Dunford, Phys. Rev. A **57**, 845, (1998).

[2] J. Eichler and W. E. Meyerhof, *Relativistic Atomic Collisions* (Academic Press, San Diego, 1995).

[3] T. Ludziejewski, Th. Stöhlker, S. Keller, H. Beyer, F. Bosch, O. Brinzanescu, R. W. Dunford, B. Franzke, C. Kozhuharov, D. Liesen, A. E. Livingston, G. Menzel, J. Meier, P. H. Mokler, H. Reich, P. Rymuza, Z. Stachura, M. Steck, L. Stenner, P. Świat, and A. Warczak, J. Phys. B. **31**, 2601 (1998).

[4] Th. Stöhlker, T. Ludziejewski, H. Reich, F. Bosch, R. W. Dunford, J. Eichler, B. Franzke, C. Kozhuharov, O. Klepper, G. Menzel, P. Mokler, F. Nolden, P. Rymuza, Z. Stachura, M. Steck, P. Świat, and A. Warczak, Phys. Rev. A **58**, 2043 (1998).

[5] S. Fritzsche, private communication.

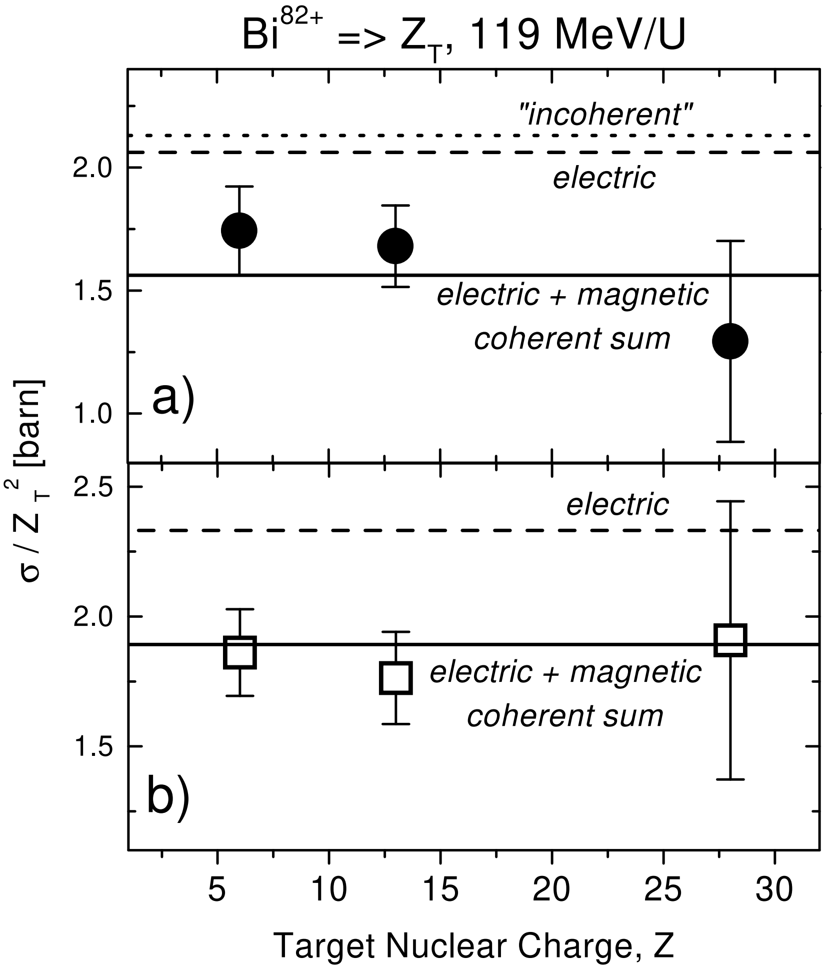

Fig. 1. Reduced (σ/Z_{T}^2) cross sections for Lyman series x-ray production in collisions of 119 MeV/u Bi^{82+} ions with C, Al, Ni solid targets; a) – Lyα_1, and b) – Lyα_2 production cross sections. The theoretical results are given separately for the complete interaction potential (——), and for the case when the magnetic part of the Liénard-Wiechert potential is neglected (— — —) [1]. In addition in a) results obtained from the incoherent sum of the electric and magnetic amplitudes are depicted ($\cdot\cdot\cdot\cdot\cdot\cdot\cdot$).

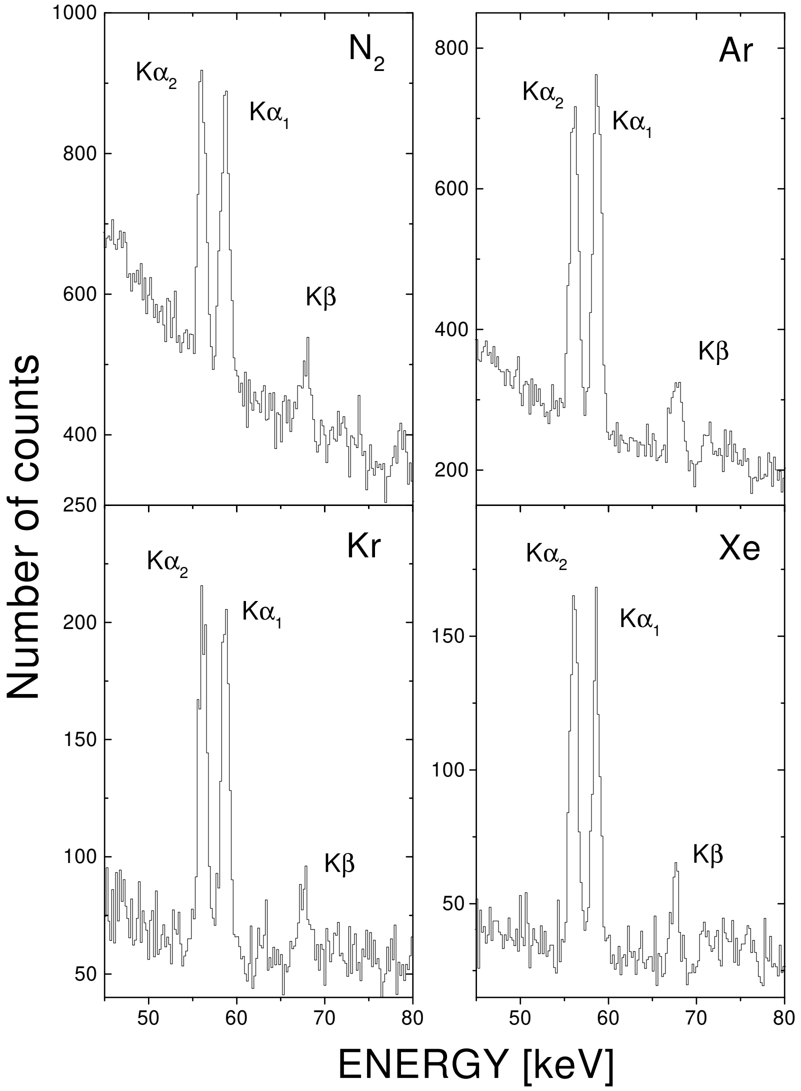

Fig. 2. Sample x-ray spectra measured at 132° for He-like U ions impinging upon the N_2, Ar, Kr, and Xe gas targets at incident energy 223 MeV/u. Only the energy region corresponding to the electron de-excitation from the L, M, and higher shells is depicted.

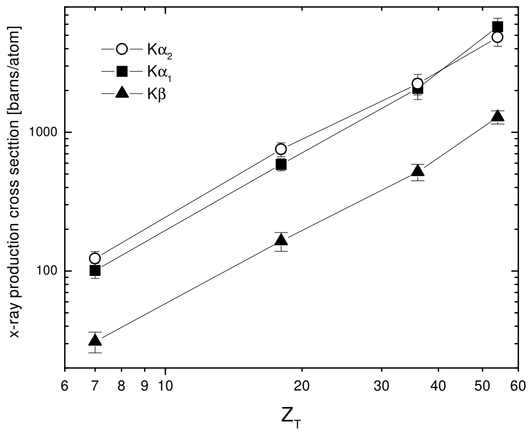

Fig. 3. Cross sections for Kα_1 (—■—), Kα_2 (—◯—), and Kβ (—▲—) production due to the ground state electron excitation by N_2, Ar, Kr, Xe gaseous targets. The error bars include estimated systematic errors.

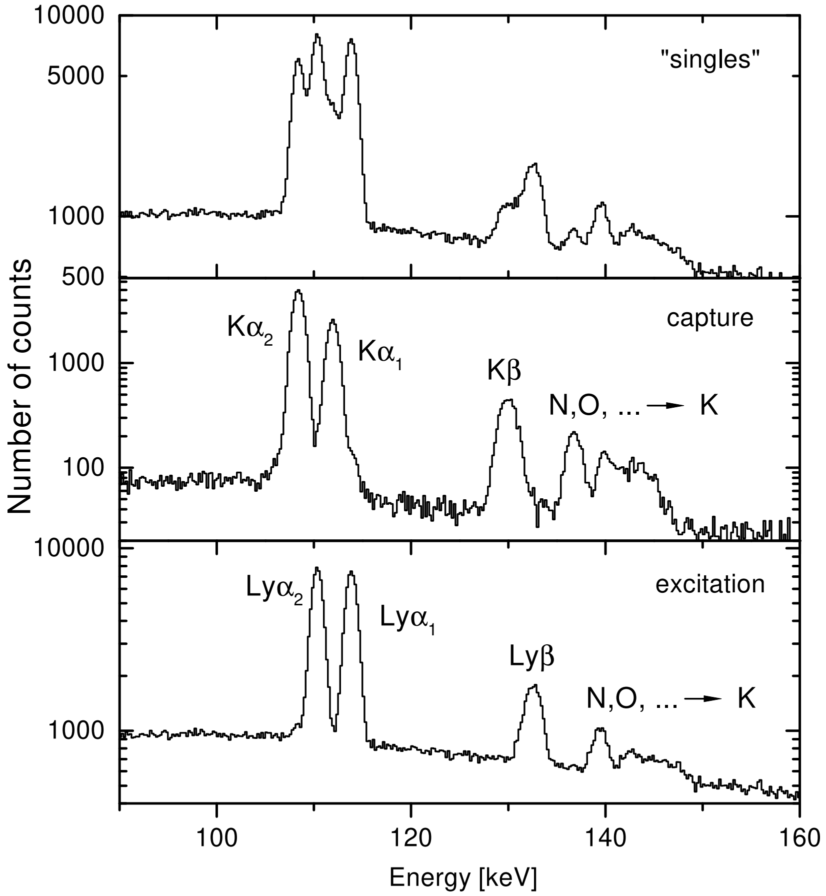

Fig. 4. Ground-state x-ray transitions measured at 35° for 256 MeV/u Au^{78+} ions colliding with Ar atoms. The upper plot represents "raw" data, the middle represent spectrum recorded in coincidence with Au^{77+} ions (capture channel). The lower spectrum represent the difference between "raw" spectrum and coincidence spectrum.