Magnetic Sublevel Population Studied for H- and He-Like Uranium in Relativistic Collisions with Low-Z Targets

A. Gumberidze[1], Th. Stöhlker[1,2], G. Bednarz[3], F. Bosch[1], S. Fritzsche[4], S. Hagmann[5], D.C. Ionescu[1,6], C. Kozhuharov[1], O. Klepper[1], A. Krämer[1,2], D. Liesen[1], X. Ma[1,7], R. Mann[1], P.H. Mokler[1], D. Sierpowski[3], Z. Stachura[3], M. Steck[1] and A. Warczak[3]

[1]GSI-Darmstadt, Germany; [2]IKF, Univ. of Frankfurt, Germany; [3]Institute of Physics, Cracow University, Poland; [4]Univ. of Kassel, Germany; [5]Kansas State University, Kansas, USA; [6]TU Dresden, Germany; [7]IMP, Lanzhou, China.

In contrast to ionization, the experimental information about Coulomb excitation of one- and few-electron projectiles occurring in relativistic atomic collisions is very scarce. The lack of data must be attributed to the experimental difficulties which arise from the fact that excitation is not accompanied by projectile charge exchange. As a consequence, this process can only be studied in single pass experiments by measuring the photon production in coincidence with primary beams of low intensity. Indeed, this technique was applied in the first experimental study of projectile K-shell excitation for high-Z ions [1, 2]. Although this experimental study already elucidated the sensitive dependence of the excitation process on the details of the relativistic bound state wave-functions in the theoretical description, the experimental results suffered from counting statistics. Very recently, an alternative experimental approach has been introduced at the storage ring ESR. Here, the formation of excited states in Au^{78+} in relativistic collisions with an Ar target by Coulomb excitation has been studied by detecting the projectile x-ray emission in anti-coincidence with charge exchange [3]. By using this technique we now started to extent our earlier investigations to a more detailed angular differential study for the collision systems U^{91+}, $U^{90+} \to N_2$ at 217 MeV/u. For x-ray detection, observation angles in the range between $\approx 10^o$ and 150^o were used at the atomic physics photon detection chamber of the internal target of the ESR (for details see Ref. [4]).

In the experiment, the projectile x-ray emission was measured in coincidence with down-charged ions as well as in a single mode, i.e. without any coincidence requirement. As a representative example we depict in Fig. 1 x-ray spectra recorded for $U^{91+} \to N_2$ collisions at the forward angle of close to 10°. In the spectra, the transitions arising from electron capture (Kα transitions in He-like uranium) and these from excitation (Lyα transitions in H-like uranium) can clearly be distinguished by both the transition energies as well as by the coincidence requirement. Indeed, no Kα transitions are observed in the anti-coincidence spectrum. This also proves that the MWPC detector used for particle detection operates with a detection efficiency very close to 100%.

In the following we concentrate on the formation of magnetic-sublevels by Coulomb excitation as well as by electron capture. Information about this topic can be obtained from the study of the angular distribution of the photons associated with these processes. For the particular case of **E1** transitions, the photon angular correlation has the form:

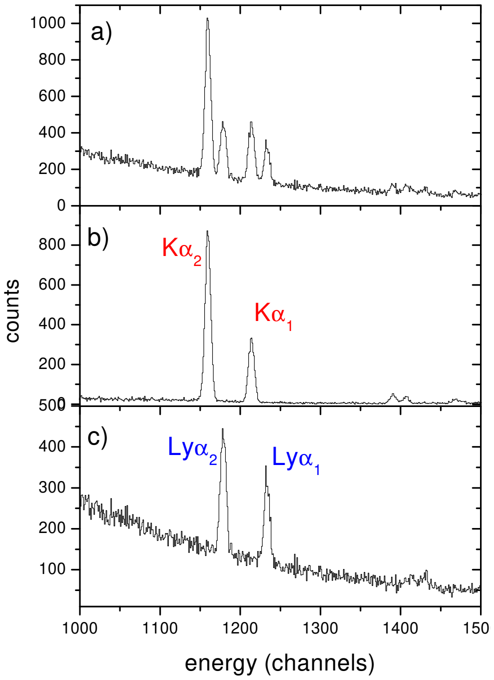

Figure 1: X-ray spectra recorded for 217 MeV/u $U^{91+} \to N_2$ collisions at the forward angle of close to 10 deg (a: total emission spectrum without coincidence requirement; b: photons in coincidence with electron capture; c: photons in anti-coincidence with electron capture).

$$W(\theta) = A_0 + A_2 P_2(\cos\theta) \propto 1 + \beta_{20}(1 - \frac{3}{2}\sin^2\theta). \quad (1)$$

Here θ is the angle between the de-excitation photon and the axis defined by the projectile motion (projectile frame) while P_2 is the second-order Legendre polynomial. The angular correlation is completely determined by the anisotropy coefficient β_{20}. In general, $W(\theta)$ is symmetric about 90° in the projectile frame and isotropic if the intermediate state has $j_n = \frac{1}{2}$ as it is the case for the Lyα_2 ($2p_{1/2} \to 1s_{1/2}$) transition. For the particular case of the $2p_{3/2}$ transition, however, one may also determine β_{20} from the alignment $\mathcal{A}_2$ of the state which is defined as

$$\mathcal{A}_2 = \frac{\sigma(\frac{3}{2}, \pm\frac{3}{2}) - \sigma(\frac{3}{2}, \pm\frac{1}{2})}{\sigma(\frac{3}{2}, \pm\frac{3}{2}) + \sigma(\frac{3}{2}, \pm\frac{1}{2})} = \frac{1}{\alpha}\beta_{20}, \quad (2)$$

where $\sigma(j = \frac{3}{2}, \mu)$ is the population of the magnetic substate with $\mu = \pm\frac{1}{2}, \pm\frac{3}{2}$. For the $2p_{3/2} \to 1s_{1/2}$ transition, $\alpha = \frac{1}{2}$. Quite similar expressions can be found

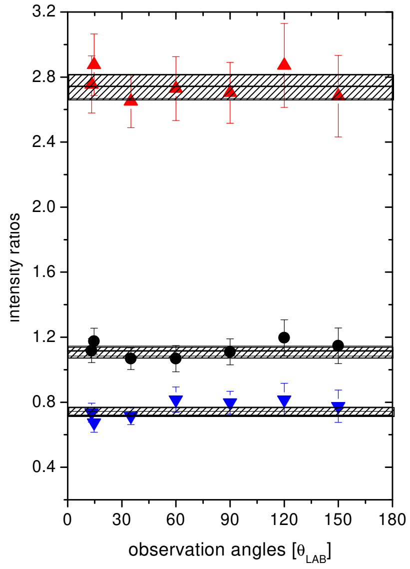

Figure 2: The intensities of Kα_2- (up-triangles), Kα_1- (solid circles), Lyα_1-transitions (down-triangles) normalized to the Lyα_2 line as function of observation angle. The experimental data were recorded for $U^{91+} \rightarrow N_2$ collisions at the energy of 217 MeV/u. The full lines refer to the corresponding mean values and the shaded areas give the associated uncertainties.

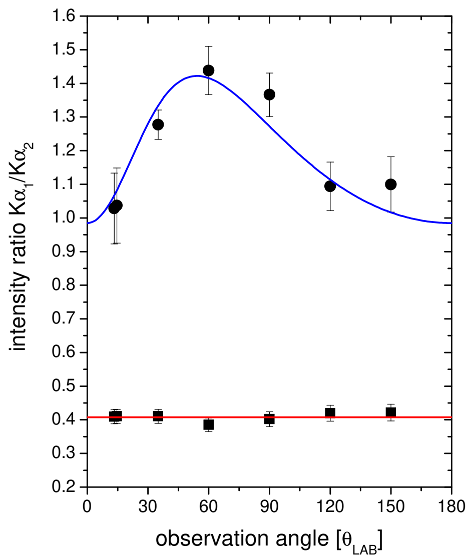

Figure 3: Kα_1/Kα_2 intensity ratio (solid circles) as observed for K-shell excitation of He-like uranium in collisions with N_2 at 217 MeV/u. The solid line refers to a least square fit of Eq. (1) to the experimental data including all required relativistic transformations. For comparison the corresponding intensity ratio (solid squares) as measured for capture into H-like uranium is shown.

for the case of the **E1** decay of the $[1s_{1/2}, 2p_{1/2}]^3P_1$ and the $[1s_{1/2}, 2p_{3/2}]^1P_1$ states in the He-like systems. Here, however, magnetic sublevels with the quantum numbers of $\mu_{J=1} = 0, \pm 1$ must be considered.

In our current experiment we strongly profited from the fact that the Lyα_2 transition arising from the decay of the $2s_{1/2}$,$2p_{1/2}$ levels is known to be precisely isotropic. Consequently, it provides an ideal tool to measure a possible anisotropy of the close spaced Lyα_1 or Kα transitions. In Fig. 2 the preliminary results for the emission pattern of the Lyα_1 and the Kα transitions are shown, normalized to the Lyα_2 intensity. In all cases no alignment is observed and the magnetic sublevels are therefore populated statistically. In the case of the Lyα_1 transition ($2p_{3/2} \rightarrow 1s_{1/2}$) induced by excitation this finding seems to be in agreement with theoretical predictions [5]. However, the isotropy of the Kα_1 emission $[1s_{1/2}, 2p_{3/2}]^1P_1, ^3P_2$, which is caused by electron capture, is in contradiction to former observations and theoretical predictions for capture into bare uranium where a strong alignment of the $2p_{3/2}$ state was observed [6]. This surprising result may point to the importance of electron-electron interaction for the emission characteristic of excited levels in high-Z He-like ions. But we have also to emphasize that the decay of two levels (**E1** decay for $^1P_1$, **M2** decay for $^3P_2$) contribute to the Kα_1 transition which cannot get resolved in our experiment. Since both transitions exhibit different angular distributions this may wipe out a distinctive anisotropy of the Kα_1 emission. Currently this topic is subject of detailed theoretical investigations.

Also for K-shell excitation we observed a markedly difference between the H- and the He-like species. In Fig. 3, the Kα_1/Kα_2 intensity ratio, as measured for K-shell excitation of He-like uranium in 217 MeV/u $U^{91+} \rightarrow N_2$ collisions, is plotted as a function of the observation angle. For comparison the corresponding intensity ratio (solid squares) as measured for capture into H-like uranium is shown in addition. In contrast to electron capture, the data for excitation exhibit a pronounced deviation from a constant intensity ratio. Note, that for the case of K-shell excitation of high-Z He-like ions, only the $[1s_{1/2}, 2p_{3/2}]^1P_1$ contributes to the Kα_1 transition whereas the Kα_2 intensity arises from the decay of the $[1s_{1/2}, 2p_{1/2}]^3P_1$ level only. In both cases an alignment of the different sublevels is possible. At present, it has not been clarified which of both states causes the observed anisotropic intensity ratio. However, at the current state of data analysis there are strong indications of a positive alignment of the $[1s_{1/2}, 2p_{1/2}]^3P_1$ level. This means that the magnetic sublevels with $\mu = \pm 1$ are preferably populated in the collision.

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