Alignment and Balmer-series of highly charged uranium in an experimental storage ring

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X-Ray spectra arising from the heaviest stable existing element uranium were observed at the experimental storage ring ESR at GSI, Darmstadt. The alignment of the $2p_{3/2}$*-state in hydrogen-like uranium and the transitions into the* $n = 2$ *state from hydrogen-like up to lithium-like uranium were analyzed.*

1 Introduction

The Experimental Storage Ring ESR at the *Gesellschaft fuer Schwerionenforschung (GSI)* in Darmstadt, Germany is a research facility partially used for atomic physics in heavy ions. A broad energy range from 10 to 400 MeV/u is accessible to examine the atomic structure of highly charged ions. With electron and stochastic cooling cold ion beams can be created for e.g. *radiative recombination (RR)* experiments at the electron cooler [1] or for *radiative electron capture (REC)* experiments at the internal gas jet target [2].

2 Alignment

Following electron capture into exited states, radiative transitions into the K-shell of Hydrogen-like ions take place (the so-called Lyman series). In the Lyman series, transitions from the L-shell have the lowest energies. They are called the Lyman α lines. For the L-shell, there are two levels with nearly equivalent energies $2s_{1/2}$ (M1) and $2p_{1/2}$ (Lyα_2) which we cannot resolve experimentally. In addition, the $2p_{3/2}$ state has to be considered. The radiation of the M1 transition is blended with the Lyα_2 radiation. This is why we obtain only two Lyα-lines in the recorded spectra.

X-Ray spectra of uranium beams with different energies are shown in figure 1. The *K-REC* and *L-REC* describes the radiative electron capture into the bound state of the $n = 1$ and $n = 2$ shell, respectively. One can describe this process as the inverse photoelectric effect (1).

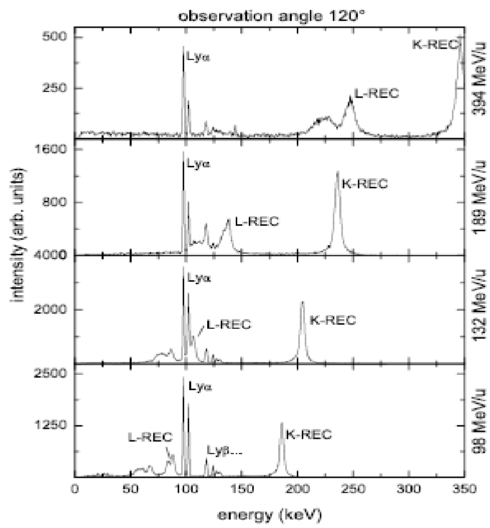

Fig. 1: *Radiation spectra of hydrogen-like uranium observed at different beam energies,* $U^{92+} \rightarrow Ar$

$$\hbar\omega = E_{kin} + E_{bin} \tag{1}$$

However, there are two Lyα lines[1] with an energy of of about $E \approx 100\ keV$. The amplitude of the Lyα_2 line is higher than the Lyα_1 amplitude in all of these spectra. The reason for the different amplitudes are apparently related to the beam velocities. Due to symmetry there is no spherically preferred direction orthogonal to the beam but the angle ϑ between beam and radiation orientation is a free parameter.

[1] $E_{Ly_{\alpha_1}} = 102.2\ keV$ and $E_{Ly_{\alpha_2}} = 97.6\ keV$ in the emitter system

2.1 Theory of Alignment

The $2s_{1/2}$ state is spherical so that the emission pattern of radiation is isotropic in the emitter-system. No direction is preferred for this magnetic dipole transition (**M1**). The $2p_{1/2}$ state (Lyα_2) and the $2p_{3/2}$ (Lyα_1) state decay via electric dipole transitions. When we split the $l = 1$ states in magnetic sub states, the $2p_{1/2}$ state has only magnetic sub-levels with $\mu = \left|\frac{1}{2}\right|$. However, the $2p_{3/2}$ state can split in two sets of magnetic quantum numbers ($\mu = \left|\frac{3}{2}\right|$ and $\left|\frac{1}{2}\right|$). The population by electron capture leads to aligned magnetic sub-levels. As a result, radiation of the $2p_{3/2} \rightarrow 1s_{1/2}$ transition is anisotropic. Following reference [2] the radiation of the $2p_{3/2}$ decay is given by

$$W(\vartheta) \propto 1 + \beta_{20}\left(1 - \frac{3}{2}\sin^2\vartheta\right) \tag{2}$$

where β_{20} is the anisotropy coefficient and describes the alignment. Note, this photon angular distribution is symmetric around 90°. To transfer the symmetrical distribution into the laboratory system a Lorentz-transformation is needed. With this transformation the maximum of the angular distribution can be observed at $\cos\vartheta_{lab} = \beta$, where $\beta = v/c$, v is the velocity of the beam and c is the speed of light. Formula 3 shows the distribution for the laboratory system.

$$\frac{\mathrm{d}\sigma(\vartheta)}{\mathrm{d}\Omega} \propto \frac{1}{\gamma^2\left(1-\beta\cos\vartheta\right)^2}\cdot \left[1 + \beta_{20}\left(1 - \frac{3}{2}\frac{\sin^2\vartheta}{\gamma^2\left(1-\beta\cos\vartheta\right)^2}\right)\right] \tag{3}$$

For the particular case of the $2p_{3/2}$ state,

$$\beta_{20} = \frac{1}{2}\frac{\sigma\left(\frac{3}{2}, \pm\frac{3}{2}\right) - \sigma\left(\frac{3}{2}, \pm\frac{1}{2}\right)}{\sigma\left(\frac{3}{2}, \pm\frac{3}{2}\right) + \sigma\left(\frac{3}{2}, \pm\frac{1}{2}\right)}. \tag{4}$$

2.2 Experiments

In a former experiment uranium-ions were accelerated in the UNILAC and SIS and injected into the ESR after stripping off all electrons. In the ESR the bare ions were cooled and decelerated to an energy of 88 MeV/u. They crossed an argon gas-jet and became hydrogen-like ions by the REC and NRC[2] process. Detectors were placed at different angles with respect to the beam axis (4°, 35°, 60°, 90°, 120° and 150°).

For normalization we take the ratio between the two Lyα-lines. Corrections due to the Doppler Shift and the first factor of the Lorentz-Transformation (see eq. 3) cancel out. The only correction needed is an efficiency correction of the detectors. This factor is also the ratio between the efficiency factor of each detector by the energy of the Lyα-lines and the Doppler shift. In figure 2 we plot the results of the ratios versus the observation angle.

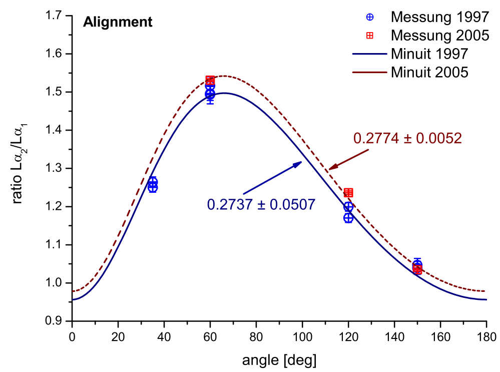

Fig. 2: *Two independent measurements (1997 and 2005) with nearly the same beam energy in the ESR,* $U^{92+} \rightarrow$ Ar

Other data from a measurement in 2005 were available too. Bare uranium was interacting on an argon gas-jet target with nearly the same energy (89 MeV/u). All ratios are plotted in figure 2. In addition, we fitted the data of both measurements with the Minuit program to extract the alignment parameter.

Tab. 1: *Alignment parameter of two independent measurements*

measurement	1997	2005
$U^{92+}\rightarrow$Ar	88 MeV/u	89 MeV/u
alignment parameter	0.2737 ±0.0507	0.2774 ±0.0052

2.3 Results and conclusion

The results for the alignment parameter are shown in table 1. If we compare both measurements with each other we will see a small dif-

[2] NRC is the non-radiative electron capture, in this process the energy of the captured electron is transfered to the nucleus of the ion.

ference in the values (about 1.3%). Considering the errors one can state that the values coincide.

3 Series

A series is a part of an electromagnetic spectrum where all transitions end in the same principle quantum number. Well known series are the *Lyman* ($n = 1$), *Balmer* ($n = 2$) and *Paschen* ($n = 3$) series. In section 2 we already mentioned two transitions of the Lyman-series (see fig. 1). In the next part we will analyze a spectrum of the same experiment. Under an angle of 35° and high amplification a Balmer-spectrum of hydrogen-like uranium was observed.

3.1 Balmer series in hydrogen-like uranium

In order interpret the spectrum in figure 3 it has to be calibrated. For calibration we took as a first reference point the end of the series where the continuum starts. This point about channel 1784 ± 30 corresponds to the maximal binding energy of the L-shell (about 34.2 keV). The second point was the first peak in the series and so the smallest transition to the $n = 2$ state. This transition is from the $3s_{1/2}$ state to the $2p_{3/2}$ state. The energy difference between both bindings energies is $29.6\ keV - 14.7\ keV = 14.9\ keV$. Before we calculate anything we transform the energies into the laboratory system. The emitter system has a beam energy of 88 MeV/u and we have to use a Doppler correction due to the finite speed of light. The correction factor for this energy is 1.37.

The peaks were fitted with Gaussian curves with the fitting routine of the *system for the analysis of tremendous amounts of nuclear data* (SATAN). Because only the center of every peak is relevant and not the area of the peaks there is no need for further corrections. Every visible peak was fitted and associated to a transition. The transitions are discrete and so peaks should be δ-peaks. In reality the finite resolution of detectors and many other effects (like uncertainty principle, ...) spread the lines into Gaussian-peaks.

However, energies divided by the Doppler shift should be conform with the theoretical transition which can be calculated. The binding energies for hydrogen-like uranium were found in [4]. The associated peaks, experimental and theoretical values are listed in table 2. The calculated and experimental data fit together.

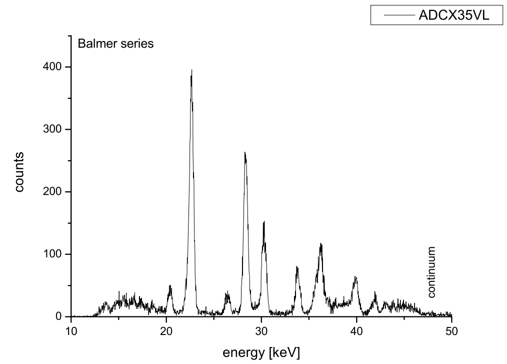

Fig. 3: *Balmer-series in hydrogen-like uranium with 88 MeV/u, NRC in an argon gas-jet target*

If the measured transition has overlap with different calculated transitions we will take the one which is not forbidden[3]. Most transitions we found are not forbidden; the angular momentum changes mostly ($d \rightarrow p$, $p \rightarrow s$ or the inverse).

3.2 L-shell series in helium- and lithium-like uranium

During the summer student program 2007 at GSI there was a beam time in our research group. During this beam time we observed M-shell spectra of transitions in helium-like and lithium-like uranium (see for example fig. 4). At the high energy part of the spectra we can see the first four L-shell lines. They have the same characteristic distribution as the Balmer series before. The same procedure like in 3.1 was applied. But first we want to talk about the experiment.

3.2.1 Experiment in August 2007

In our experiment we had an uranium beam with different energies and charged states (U^{91+} and U^{90+}). The beam crossed the gas-jet target of nitrogen N_2 and captured an electron. Radiation was detected under different angles. At 90° inside the ring there was a crystal spectrometer to measure Bragg reflection at about

[3] Forbidden means the angular momentum l of the transition does not change. This is forbidden because the photon takes an angular momentum of the value one away.

Tab. 2: *Binding energies associated with transitions in a Balmer series*

peak	$E_{labor\ system}$	$E_{emitter\ system}$	$E_{transition}$	transition
1	$20.40\ keV \pm 0.44\ keV$	$14.88\ keV \pm 0.32\ keV$	$15.00\ keV$	$3s_{1/2} \rightarrow 2p_{3/2}$
2	$22.65\ keV \pm 0.43\ keV$	$16.53\ keV \pm 0.32\ keV$	$16.68\ keV$	$3d_{5/2} \rightarrow 2p_{3/2}$
3	$26.45\ keV \pm 0.60\ keV$	$19.30\ keV \pm 0.44\ keV$	$19.48\ keV$	$3s_{1/2} \rightarrow 2s_{1/2}$
4	$28.35\ keV \pm 0.43\ keV$	$20.69\ keV \pm 0.31\ keV$	$20.82\ keV$	$3p_{3/2} \rightarrow 2s_{1/2}$
end	$46.90\ keV \pm 0.50\ keV$	$34.23\ keV \pm 0.36\ keV$	$34.20\ keV$	continuum

$4.5\ keV$. At 90° at the outer side there was a 2D Si-detector to measure the Compton scattering. An ORTEC Ge-Detector was placed under 35°. The spectra are results of this detector with a beam energy of $43.55\ MeV/u$ (charge state: 91^+) and $32.6\ MeV/u$ (charge states: 90^+).

3.3 Results and conclusion

After the analysis of the peaks and data[4] there are about 11 peaks in the M-shell series and 4 peaks in the L-shell series in the spectrum of helium-like uranium (4). It is very difficult to analyze the data, because it is no longer a two body problem. The second electron partially shields the nucleus and the captured electron sees a smaller charge state of the nucleus. A rough correction for the comparison with hydrogen-like uranium is the ratio of squared charge states (for example $[92/90]^2$). The idea is that every electron shields the charge of $1e$ of the nucleus. For L-shell series in helium- and lithium-like uranium the results fit with theoretical differences of the binding energies (see tab. 3).

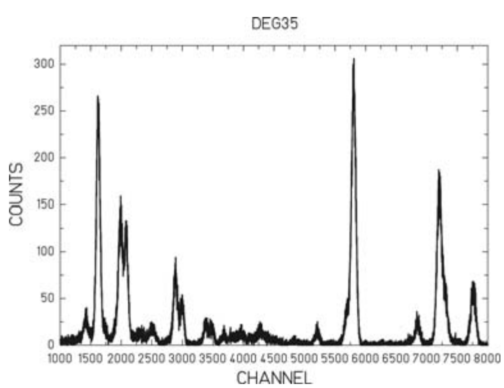

Fig. 4: *M- and L-shell spectrum obtained in an experiment in August 2007,* $U^{90+} \rightarrow N_2$, $32.6\ MeV/u$

To interpret the characteristic M-shell spectrum we need new correction factors for transitions in helium- and lithium-like uranium. Experimental data of our experiment can give new values for the binding energies in helium-like uranium to develop the theory and to test higher orders of a perturbation theory.

[4] The calibration of the Ge-detector was done with an iron and an americium source.

Tab. 3: *L-shell series in helium- and lithium-like uranium with Doppler shift and shielding correction and the theoretical transition in hydrogen-like uranium*

$E_{transition}$ in [keV]		
experimental		theoretical
U^{90+}	U^{89+}	U^{91+}
14.959 ± 0.007	14.957 ± 0.003	14.998
16.675 ± 0.001	16.677 ± 0.001	16.682
19.581 ± 0.005	19.689 ± 0.003	19.485
20.816 ± 0.001	20.763 ± 0.001	20.824

Acknowledgments

At the end I want to thank the whole group for the possibility to work with them and especially Thomas Stoehlker for supervising me. It was a great experience to work in atomic physics. Also many thanks to Joern Knoll, Heide Rinnert and their team for organizing the summer program and helping if something was going wrong.

References

[1] R. Reuschl et al. / Radiation Physics and Chemestry **75** (2006) 1740-1743

[2] Th. Stoehlker et al. / Phys. Rev. Lett. **79**, 3270 (1997)

[3] Th. Stoehlker et al. / The Lyman -α_1 Decay in hydrogen-like ions: Interference ...

[4] P. Indelicato / private communication (1998)