State Selective Electron Capture Studies: The Contribution of M1- and E2-Transitions to the Lyman Radiation of H-like Uranium *

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The heavy-ion storage ring ESR provides the unique possibility to decelerate highly charged ions up to bare uranium to energies which are far below the energy required for the efficient production of high charge states. This technique allows for a detailed study of atomic collision dynamics and, in particular, for a (n,l,j)-sensitive investigation of electron capture processes by means of x-ray spectroscopy. The results of a first state selective capture investigation performed for decelerated bare uranium ion are discussed and their relevance for Lamb shift investigations on high-Z hydrogenlike ions is emphasized.

34.70.+e, 31.30.Jv, 31.50.+w

*Dedicated to Prof. Dr. Karl-Heinz Schartner on the occasion of his 60^{th} birthday.

I. INTRODUCTION

The capability of the ESR storage ring to decelerate bare high-Z ions to low collision velocities opens up new challenging perspectives for both the fields of atomic structure and collision research. The benefit for atomic structure studies lies in the strongly reduced Doppler effect and its associated uncertainties [1]. Similar, the study of atomic collision dynamics profits considerably from the enhanced resolution due to the reduced Doppler broadening [2]. Along with the large fine structure splitting in high-Z ions this even allows to resolve the line splitting of the Lyman-β transitions. Moreover, at low energies, a multitude of intense and well resolved Balmer transitions show up in the spectra providing complementary information to the Lyman transitions. This has been demonstrated within the first experiment with decelerated ions conducted at the ESR, where the x-ray emission of bare uranium ions was studied in collisions with a N_2 gas-target [1]. An extensive analysis of the measured Balmer spectra proved, that the relative intensity distribution of the Balmer series observed is a sensitive probe for the (n,l,j)-distribution of electron capture [3]. In particular, by considering correct relativistic transition rates and theoretical subshell-differential cross sections, on the basis of the Eikonal approximation for non-radiative electron capture [4], an excellent agreement between the experimental data and this theoretical model was found [5]. In the following we extend this study to the simultaneously observed Lyman-transitions. Here, the key issue addressed is the occurrence of higher-multipole radiation (**M1** and **E2**) which may considerably contribute to line intensities of the observed ground state transition in high-Z ions. The great importance of this issue for spectroscopic studies is evident since **M1** – and **E2** – radiation, arising from the decay of the $ns_{1/2}$ ($n \geq 2$) and $nd_{3/2,5/2}$ ($n \geq 3$) levels, leads to a contamination of the $np_{1/2}$ ($n \geq 2$) and the $np_{3/2}$ ($n>2$) x-ray lines, a contamination which presently cannot be resolved experimentally. However, assuming that the Lyman-β radiation stems only from the **E1** decay of p-states, the Ly-α_1 – Ly-$\beta_{1,2}$ energy differences are precisely known since they are almost not effected by QED corrections. Therefore, they would allow for an intrinsic Doppler correction of the spectra measured for H-like high-Z.

Such a technique would considerably improve the precision currently reached in 1s Lamb shift experiments for high-Z H-like ions. Consequently, there is an urgent need for a detailed investigation of the role of higher-order photon emission in high-Z H-like ions.

II. RESULTS AND DISCUSSION

A typical Lyman spectrum measured for decelerated bare uranium ions is displayed in Fig. 1. The spectrum was recorded in coincidence with electron capture for initially bare uranium ions colliding with N_2 molecules at the energy of 68 MeV/u. As observed in the spectrum, the j-subshell splitting of Ly-α and Ly-β lines appears well resolved. Moreover, the simplified level scheme given in addition illustrates the origin of the Lyman transitions up to n=3 along with their multipolarity. The **M1** transition from the $2s_{1/2}$ level is well known since for the case of H-like uranium it constitutes by far the dominant decay channel of this particular level in high-Z ions. In contrast, the **E2** transitions from the d- states were not considered since they contribute by only 2% to the total decay rate. However, they still may contribute significantly to the intensity of the Lyman lines since the total population cross section must be considered in addition. To show this, the experimental spectra were simulated by the same model as applied for the analysis of the Balmer transitions [5]. Here, the cross sections for capture into all the individual (n,l,j)-levels were calculated first. For this purpose the process of radiative electron capture was considered by complete relativistic calculations [6] up to n=5. For higher states, the non-relativistic dipole-approximation was used. In order to account for the non-radiative capture process, the Eikonal approach was applied and the calculations were extended up to states with principal quantum number as high as n=40. Finally, cascade calculation had to be performed. Here, exact relativistic transition rates were considered in the framework of the Dirac theory for all the states up to n=7. For all the higher levels, only electric dipole transitions were taken into account. As an example, we compare in Fig. 2 the Lyman-$\beta, -\gamma, ...$ spectrum, measured at 68 MeV/u, with the result of the discussed spectrum analysis. For comparison, the theoretical spectrum was adjusted to the experimental one by using one fit-parameter for the spectrum amplitude. From the figure, a good agreement between the experimental data and the theoretical result can be stated. Moreover, the applied analysis technique allows us to depict the **E2** contribution (shaded area) transitions separately in the figure. The latter is found to contribute significantly to the observed line intensity (about 30% at 68 MeV/u) for the Ly-β_1 radiation. This surprising finding can be explained by the (n,l,j)-distribution of the NRC process. For decelerated ions, it constitutes the most important capture process which populates preferentially high (n,l)-states.

III. CONCLUSION AND SUMMARY

Subshell sensitive investigations for electron capture into decelerated bare uranium ions were performed in order to study the importance of higher-multipole contributions to the Lyman transitions in H-like uranium. In particular, the results of our data analysis show, that the measured intensity distribution of the Lyman Series in U^{91+} can only be explained if **E2**-transitions from d-states are considered. Therefore, the use of the Ly-α_1 – Ly-$\beta_{1,2}$ energy splitting for an intrinsic Doppler correction in experiments aiming at a precise determination of the 1s- Lamb shift in H-like high-Z appears to be questionable. Here, the contamination of the unresolved **E2**-transitions may lead to an appreciable energy shift of the Lyman-β line centroids where it is commonly assumed that only transitions from the two 3p-states contribute. However, the absolute strength of the found contamination by **E2**-transitions can only be approximately calculated since alignment effects are not considered up to now. In this respect, the **E2** transition of $3d_{5/2}$ level to the 1s ground state is most problematic since its transition energy differs by as much as 345 eV from the one of the $3p_{3/2}$ state. We have to add that on the basis of the applied spectrum analysis, also the **M1**-contribution to the Ly-α_2 radiation was determined and can now be given as a function of the beam energy for $U^{92+} \rightarrow N_2$ collisions. Since the latter one is a j=1/2 $\rightarrow$ j=1/2 transition, alignment effects are completely absent which allows us to predict the combined **M1**-Lyα_2 centroid energy with a precision close to 2 eV.

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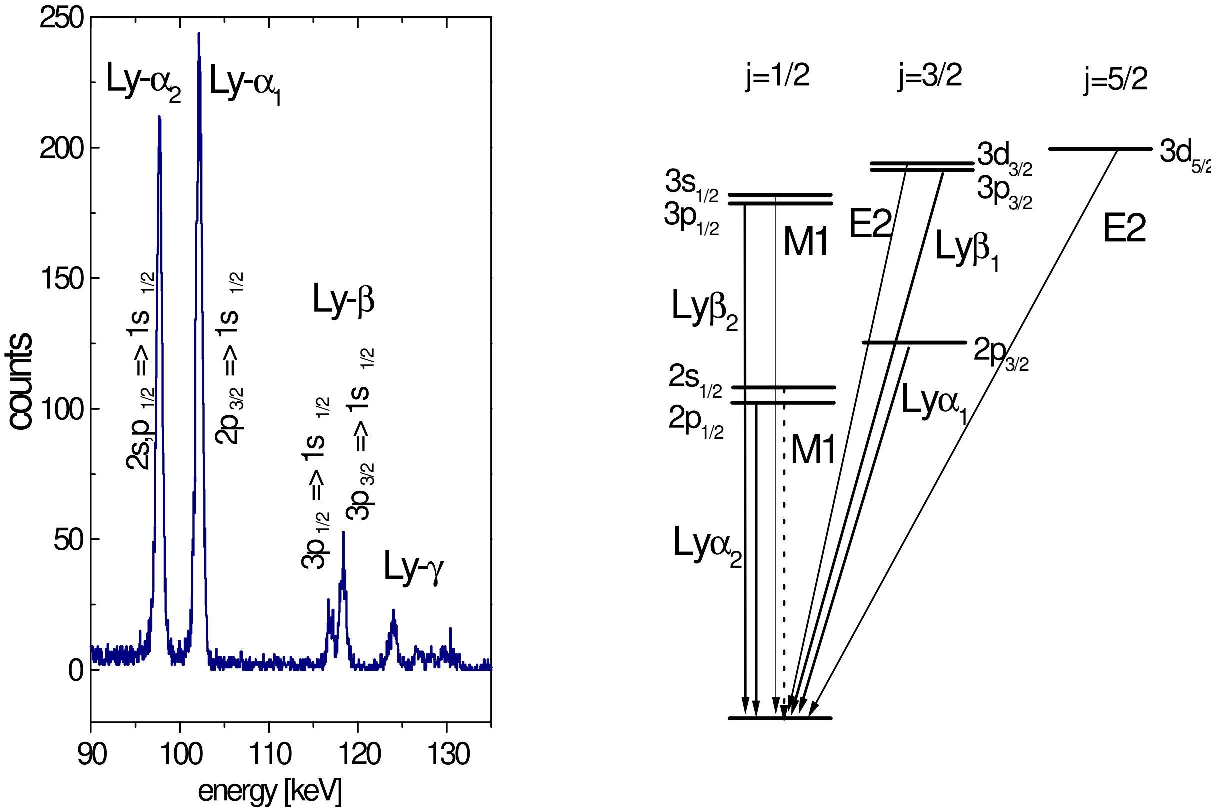

FIG. 1. Lyman spectrum of H-like uranium measured for $U^{92+} \rightarrow N_2$ collisions at 68 MeV/u in coincidence with electron capture. In addition, a simplified level scheme is given which illustrates the origin of the Lyman transitions up to n=3.

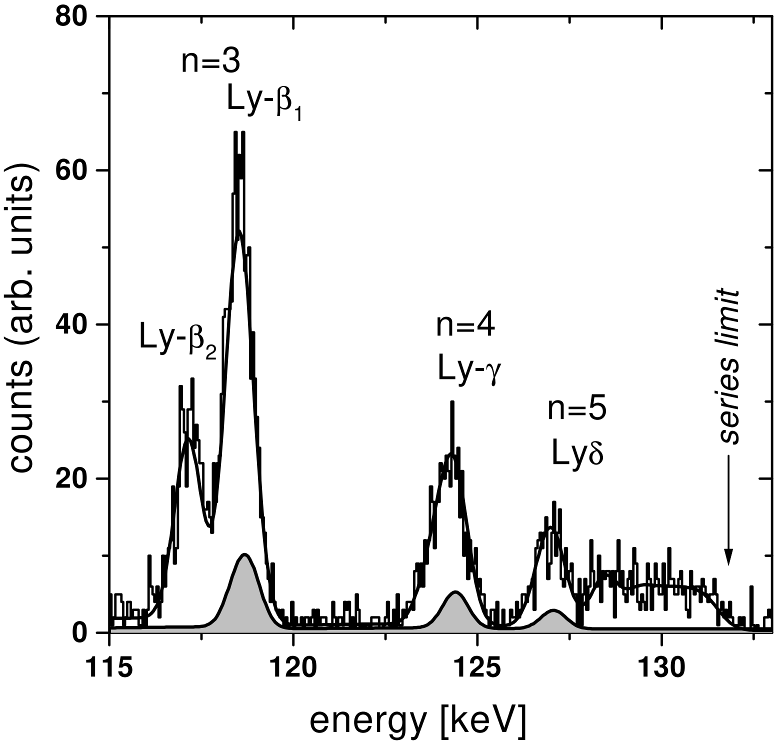

FIG. 2. The Lyman-$\beta, -\gamma, ...$ spectrum measured at 68 MeV/u in comparison with the result of the discussed spectrum analysis (full line). The shaded area depicts the **E2** contribution.