Investigation of the Decay Properties of the 1s(2s)² State in Li-Like Uranium

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Abstract. We report on an experiment aiming for a study of the radiative decay modes of the 1s(2s)² level in Li-like uranium. The experiment was performed of initially Be-like uranium colliding with N₂ molecules at an energy of 90 MeV/u. By measuring the x-ray production associated with K-shell ionization of the projectile, a high selectivity for the production of the 1s(2s)² level is observed.

1. Introduction

Since recent years, the decay properties of the singly excited 1s(2s)² state in Li-like ions has been the subject of detailed experimental and theoretical investigations [1,2,3,4] (and for a survey see Ref. [5]). The particular feature of this state is the occurrence of an exotic, dipole allowed two-electron one-photon decay (TEOP) into the (1s)²2p1/2 and the (1s)²2p3/2 levels, mediated by configuration interaction. At low Z, the TEOP decay gives only a minor contribution to the total decay rate, which is dominated by the autoionization channel. However, it already contributes significantly to the total decay probability at Z around 30 and is predicted to be the dominant decay channel for the highest nuclear charges such as Z=92. In the latter case, the magnetic dipole radiative decay into the (1s)²2s ground state must be considered in addition (the various decay modes of the 1s2s² ²S1/2 state as function of the atomic number Z are given in figure 1 [5]). This strong variation of the decay properties of the 1s(2s)² state along the isoelectronic sequence is therefore an ideal testing ground for our understanding of the interplay of relativistic and correlation effects on the atomic structure of few electron systems. However, up to now the experimental information about this topic is limited to nuclear charges smaller than 50.

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Here, we report on an experiment aiming for a study of the radiative decay modes of the $1s(2s)^2$ level in Li-like uranium by adopting a state selective population technique as introduced recently [6,7], allowing us to produce almost exclusively the $1s(2s)^2$ level. This technique utilizes the x-ray production by K-shell ionization of high-Z projectiles as it occurs in collisions with gaseous targets, which was found to be a highly-selective mechanism for the population of excited ($n=2$) $s$-states. As an example, it allowed for a selective production of the two singly excited $s$-levels of He-like uranium by K-shell ionization of the Li-like species.

![Diagram](image-url)

**Figure 1.** Rates for the various decay modes of the $1s2s^22S_{1/2}$ state as functions of the atomic number $Z$ [5].

2. Experiment
The experiment was performed at the experimental storage ring ESR at GSI-Darmstadt. For the experiment, uranium ions with an energy of 90 MeV/u have been provided by the SIS synchrotron. After acceleration to the final energy, the Be-like charge state was produced by using a thin carbon stripper foil, with a thickness much below the equilibrium thickness, which allowed us to achieve a high production yield for the Be-like ions. Behind the foil the beam was magnetically analyzed, and the fraction of $\text{U}^{88+}$ ions was transferred into the ESR storage ring. Typically, $10^8$ ions were stored and electron cooled in the ring. For the purpose of cooling, the ESR electron cooler was operated with electron currents in the range between 100 mA and 200mA. After the cooling cycle, the accumulated ions, forming a beam with a full width at half maximum of about 2 mm, were colliding with a supersonic gas-jet N$_2$ target having a typical area density of about $10^{12}$ atoms/cm$^2$. The beam energy loss, caused by the interaction of the beam with the target atoms, was compensated by the continuous electron cooling. The x-rays following the collisions of the ions with the target were registered by an array of germanium detectors covering observation angles from ~0° to 150° with respect to the beam direction. After passing through the target area the projectiles which lost or captured one electron were registered upstream behind the next bending magnet of the ring with an efficiency close to 100%. Up-charged and down-charged uranium ions were detected by two position sensitive particle detectors (Multi-Wire Proportional Counters) located at the inner and outer side of the ring, respectively. For a detailed description of the setup used we refer to the literature [8]. The time signals of the x-ray detectors served as a trigger and no hardware coincident event selection was used. By an analysis of
the time information, this trigger technique allowed us to reconstruct those x-rays that were coincident or anti-coincident with projectile charge exchange from the list mode data [8].

Figure 2. Preliminary x-ray spectra recorded at the observation angle of 35 degree for 90 MeV/u U$^{88+}$ → N$_2$ collisions.

3. Discussion
In figure 2, we present preliminary x-ray spectra as recorded at an observation angle of 35 deg. By the timing technique applied, the x-rays associated with K-shell excitation (no projectile charge exchange, anti-coincidence) is disentangled from events where x-rays are produced by K-shell ionization (coincidence with up-charged projectiles). As can be seen in figure 2, K-shell ionization appears again to be a very selective population process (compare the results for He-like ions [6,7]). In the associated photon spectrum only one single x-ray line is observed stemming from the decay of the 1s(2s)$^2$ state. We have to point out, that in contrast to low-Z ions, this state may also decay by a fast M1 transition. This is depicted in figure 3 where, for the particular case of U$^{89+}$, the various decay modes and decay energies of the 1s(2s)$^2$ state are given. Interestingly, for the case of uranium, the TEOP into the (1s)$^2$2p$_{1/2}$ level is predicted to be the dominant decay mode. Also, one may note, that in contrast to low-Z (see figure 1), the TEOP into the (1s)$^2$2p$_{3/2}$ level is predicted to be negligible. Indeed, no such transition appears to be visible in the recorded spectrum, which should show up well separated, by about 4 keV, from the dominant line.

Currently, the data evaluation is in progress. Because we are presently not able to separate experimentally the two decay branches, TEOP and M1, the goal of the present analysis is to determine M1/TEOP branching ratio, i.e. the contamination of the TEOP by the M1 decay, using an accurate line centroid determination of the observed x-ray line. The energy separation between the two transitions of interest amounts, within the emitter frame, to be close to 280 eV. For redundancy, one may use the corresponding energies of the K$\alpha_1$, K$\alpha_2$ lines, produced by excitation, as an energy reference to
estimate the contamination of the TEOP by the M1 decay. The latter provides an important cross-check for the Doppler corrections to be applied. Of course, this is based on the assumption that K-shell excitation of the Be-like ions occurs to the 1s2s2p3/2 and 1s2s2p1/2 levels exclusively. Moreover, we would like to emphasize that in total 5 different x-rays detectors, positioned under different observation angles have been used. The final result should be consistent with the data provided by all the different detectors.

4. Summary
In summary, an experimental investigation of the radiative decay modes of the 1s(2s)2 state in Li-like has been started. In the first beam time at the ESR storage ring devoted to this topic, we succeeded to populate selectively this state via K-shell ionization of the initially Be-like species. The x-rays produced in this process were measured by a multitude of x-ray detectors, each placed under different angles. The spectra associated with projectile electron loss consist in all cases out of one single x-ray transition, which we attribute to the TEOP decay to the (1s)22p1/2 level, possibly contaminated by the M1 decay to the (1s)22s. Due to the lack of high resolution x-ray detectors within the current investigation, the goal of the current data analysis is to determine the M1/TEOP branching ratio from an accurate line position determination from the x-ray feature observed in the spectra, which should allow us to obtain the contamination by the M1 line.

In the near future we plan to extend this study by the inclusion of an electron spectrometer currently commissioned at the ESR [9]. This would allow us to measure in addition the autoionization channel, providing us with the complete information of the various decay modes for the 1s(2s)2 state.

![Level scheme and decay modes of U89+. The transition energies and the radiative rates are taken from [5]. The numbers in brackets indicate power of 10.](image)

**Figure 3.** Level scheme and decay modes of U89+. The transition energies and the radiative rates are taken from [5]. The numbers in brackets indicate power of 10.

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