Study of intra-L shell transitions in Be-like uranium

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Abstract. The x-ray spectra produced in collisions of 98 MeV/u Li-like uranium ions with \( \text{N}_2 \) molecules have been studied. By measuring the decay photons associated with the capture process, experimental information for the formation of the excited \([1s^22s2p^3/2]_1^1P_1\) and \([1s^22s2p^3/2]_3^3P_2\) states in Be-like uranium has been obtained. It was found that relative probability for production of the \( P \)-states is close to statistical population law \( 2J + 1 \).

1. Introduction

In collisions of few electron heavy ions with low-Z target atoms, the projectile may lose or capture an electron into a bound state. Recently we have studied the formation of singly excited \([1s^22s]_1^1S_0\) and \([1s^22s]_3^3S_1\) states in He-like uranium by K-shell ionization of the initially Li-like species colliding with nitrogen atoms/molecules \cite{1}. Here we report on a population of singly excited \( n = 2 \) \( P \)-states in Be-like uranium produced in electron capture of the (initially) Li-like ions colliding with nitrogen atoms/molecules corresponding to the atomic reaction

\[
\text{U}^{89+} + \text{N} \rightarrow \text{U}^{88++} + \text{N}^+ \rightarrow \text{U}^{88+} + \hbar \omega + \text{N}^+, \tag{1}
\]

where \( \text{U}^{88+} \) refers to a singly excited Be-like ion produced within the collision, and \( \hbar \omega \) represents intra-L shell transitions, respectively. If an electron is captured into the \( 2p_{3/2} \) orbital the \([2s2p_{3/2}]_1^1P_1\) and \([2s2p_{3/2}]_3^3P_2\) states of Be-like uranium can be populated. Only the state with \( J = 1 \) can deexcitate to the ground state \( (J = 0) \) of the beryllium-like uranium by an E1 transition (see figure 1). In the case of the \([2s2p_{3/2}]_1^1P_1\) \( (J = 2) \) level, the deexcitation to the \([1s^22s^2]_1^1S_0\) ground state is not electric-dipole-allowed. Such state can deexcitate via M1 transition. The transition probabilities of the other deexcitation channels (E2 and M2) are two orders of magnitude smaller than the M1 decay rate \cite{2}.

Studies of the intra-L shell transitions are interesting in several respects. Such transitions are sensitive to both intrashell and innershell interactions. For the intra-L shell transitions in Be-like species, the relative QED contributions to the total transition energy are much higher (10\%)}
than for the K x-ray transitions (0.5%) [3]. The study of high-Z Be-like ions is of particular interest for spectroscopic diagnostics of high temperature plasmas in tokamaks [4]. Finally, the $2p_{3/2} - 2s_{1/2}$ and $2p_{1/2} - 2p_{1/2}$ intra-L shell transitions give quantitative information on the population of $P$-states formed by the electron capture processes. Therefore in recent years the transitions in Be-like ions were subject of intensive studies [3, 5, 2, 6].

2. Experiment and results

In order to investigate the intra-L shell decay of the $[2s2p_{3/2}] \ ^1P_1$ and $[2s2p_{3/2}] \ ^3P_2$ states produced in electron capture, measurements of the x-ray spectra produced in collisions of 98-MeV/u Li-like uranium with gaseous N$_2$ target have been performed at the experimental storage ring ESR at GSI-Darmstadt. The Li-like charge state was obtained after acceleration to the final energy by using a Cu stripper foil (50 mg/cm$^2$). Downstream of the foil, the beam was magnetically analyzed and the U$^{89+}$ ions were injected into the ESR storage ring. Typically, 10$^8$ ions were stored and electron-cooled in the ring. The electronic configuration of the Li-like ions used in the experiment correspond to the ground state due to the absence of long-living metastable states. After the cooling cycle, the supersonic gas-jet N$_2$ target with area density of about 10$^{12}$ particle/cm$^2$ was switched on, producing a well collimated beam (5 mm in diameter) which intersects the ion beam trajectory.

The x-ray spectra produced in collisions of Li-like uranium with an N$_2$ gas target were measured by planar Ge(i) detectors surrounding the jet target at observation angles close to 10°, 35°, 60°, 90°, 120° and 150° with respect to the beam axis, in coincidence with down- and up-charged uranium ions. Figure 2 shows x-ray spectra measured in the experiment at the angle of 90°. The spectra refer to the laboratory frame and are not corrected for detector efficiency.

In the Fig. 2(a) the total x-ray spectrum is presented. This spectrum originates from excitation, ionization and capture processes which occur during relativistic ion-atom collision. In the spectrum associated with ionization (see [1]) only one sharp line and the broad continuum ranging from 0 keV up to 130 keV appear. This structure of the spectrum suggests that K-shell ionization is a very selective process leading to the formation of only the $[1s2s] \ ^1S_0$ and $[1s2s] \ ^3S_1$ states which decay via two photon $2E1$ and magnetic $M1$ transitions, respectively. By measuring the angular distribution of these transitions we have obtained the relative probabilities for the formation of the $S$-states. The average experimental $2E1/M1$ intensity ratios obtained for two different energies deviates considerably from the assumption of a statistical population $2J + 1$ and they are in fair agreement with the simplified assumption of the sudden approximation.
Figure 2. Projectile x-ray spectra for 98 MeV/u U$^{89+}$ → N$_2$ collisions measured (a) without coincidence (total emission spectrum) and (b) in coincidence with electron capture (U$^{88+}$). Both spectra were recorded at an observation angle of $\theta = 90^\circ$.

Figure 3. Low energy region of the x-ray spectrum for 98 MeV/u U$^{89+}$ → N$_2$ collisions measured with electron capture coincidence (U$^{88+}$ charge) recorded at the ESR storage ring at an observation angle of $\theta = 35^\circ$.

In the Fig. 2(b) the corresponding spectrum associated with electron capture (outgoing charge state of U$^{88+}$) is shown. In the high-energy region of this figure, the observed radiation is dominated by radiative electron capture (REC) into the M-shell of the projectile. Due to the filled K-shell, no K$\alpha$, $\beta$, ..., emission is visible within this spectrum. In the low energy region of the spectrum associated with electron capture (see Fig. 3) one can see strong intra-L shell transition E1 and M1, respectively. These $\Delta n = 0$ transitions correspond to the deexcitation of the $[2s2p_{3/2}]^1P_1$ and $[2s2p_{3/2}]^3P_2$ states to the $[1s^22s^2]^1S_0$ ground and $[2s2p_{1/2}]^3P_1$ excited states of beryllium-like uranium, respectively (see Fig. 1). Note that the theoretical lifetimes of these two states differ by two orders of magnitude. In order to obtain relative probabilities for the formation of the P-states in electron capture process we have analyzed the intensity ratios of the intra-L shell $2p_{3/2} \rightarrow 2p_{1/2}$ (M1) and $2p_{3/2} \rightarrow 2s_{1/2}$ (E1) transitions of Be-like uranium for two different observation angles. The previous experimental results are presented in Fig. 4. We have found that the relative probabilities for the formation the $^1P_1$ and $^3P_2$ following electron capture process are close to the ratio of a statistical population $2J + 1$, an observation consistent with earlier studies performed for initially He-like uranium ions [8]. At the present status of the analysis we can not distinguish each individual contribution to the production of a given P-state. In order to obtain such information one should take into account electron capture into higher than $n = 2$ states and then following cascade transitions to the $n = 2$ P-states. Since, for the 98-MeV/u
U^{89+} + N collision the theoretical nonradiative electron capture (NREC) [7] into the L-shell is much smaller than capture into M, N and higher shells ($\sigma_L/\sigma_{M,N,...} \approx 0.06$), the cascade transitions can considerably influence on the $P$-state population. In addition, radiative electron capture has to be considered.

3. Summary

The intra-L shell transitions of Be-like uranium induced in relativistic collisions of initially Li-like uranium ions with $N_2$ target molecules have been studied. It was found that in contrary to the K-shell ionization process which leads to non-statistical formation of the S-states, the electron capture processes populate the $^1P_1$ and $^3P_2$ states with a statistical distribution $2J+1$. For more detailed studies of the formation excited states in electron capture processes further experimental and theoretical studies are needed. Future analysis should take into account electron capture into the highly excited states of the Be-like species as well as cascade transitions from these states.

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