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Isomeric state of ^{80}Y and its role in the astrophysical rp-process

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Abstract. A careful investigation of the isomeric transition of the long-lived state at 228.5 keV excitation energy in ^{80}Y has been done. The HIGISOL facility at the Jyväskylä isochronous cyclotron has been used. We used the electron magnetic transporter to prepare an appropriate source and to measure the electron spectra in clean background conditions. The measured internal conversion coefficient $\alpha_K = 0.50 \pm 0.07$ allows unambiguous 1^- identification for the 228.5 keV first excited isomeric state in ^{80}Y. With a "bare" half-life of 6.8 ± 0.5 s found in this work, this state is strongly populated in the rp-process during X-ray bursts and has therefore to be taken into account in X-ray burst model calculations. However, because of the similarity of the β-decay half-lives of isomeric and ground states, we find a maximum reduction in the effective β-decay lifetime of ^{80}Y of only $17 \pm 2\%$. Our results pave the way for a future investigation of the impact of the isomeric state on the "effective" ^{80}Y proton capture rate.

PACS. 21.10.Tg Lifetimes – 23.20.Nx Internal conversion and extranuclear effects – 27.50.+e $59 \leq A \leq 89$

The region of very extreme neutron-deficient nuclides at the mass number $A \approx 80$ is a subject of particular interest. The problems of $Z = N$ nuclides, position of the proton drip-line and dramatic shape changes are intersecting there. The region is of specific interest for astrophysics because the rp-process in X-ray bursts is passing through it (see fig. 1) [1].

^{80}Y is one in a series of odd-odd $T_z = 1$ nuclides in the rp-process, where rapid proton capture resumes after a considerable delay caused by the β-decay of the even-even $N = Z$ waiting point parent, in this case ^{80}Zr. ^{80}Y is also part of the Zr-Nb-Mo cycle that would occur for the low α separation energies predicted for ^{84}Mo by the Finite Range Droplet Mass Model FRDM92 under certain conditions (see ref. [1]). While the lifetime of ^{80}Y during most of the rp-process is very small due to fast proton captures, it becomes a critical parameter during freezeout when proton capture rates are lower because of decreasing temperatures and hydrogen exhaustion. During freezeout the interplay of ^{80}Y proton capture and β-decay determines how many of the $A = 80$ nuclei accumulated at the ^{80}Zr waiting point during the rp-process remain in the $A = 80$ mass chain and ultimately decay into stable ^{80}Kr. This is of considerable interest because the large overproduction of the s-process nuclide ^{80}Kr strongly constrains the possible importance of the rp-process as a source of light p-nuclides [1].

The recent discovery of isomeric transitions in ^{80}Y with energies 228.5 keV [2] and 84 keV [3] stimulates an additional interest in this nuclide. Isomeric states can play a critical role in the rp-process, as proton capture rate and β-decay lifetime can be different than those of the ground state. Therefore for accurate rp-process calculations, excitation energy, decay modes, spin and parity of isomeric states need to be known. The role of an isomer depends also on the feeding mechanism and the presence of medi-

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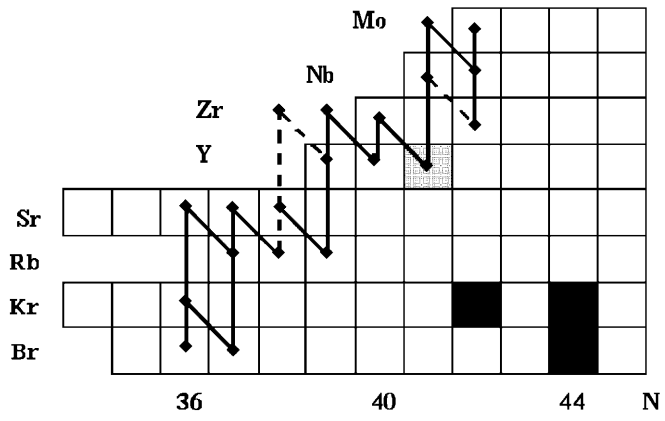

Fig. 1. Expected [1] rp-process path in the region of mass number $A = 80$. Black squares stand for the stable nuclides. The grey square indicates the nuclide ^{80}Y studied in this work.

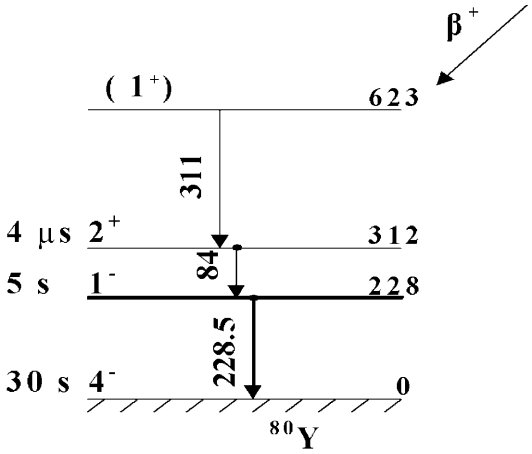

Fig. 2. Excited states of ^{80}Y observed [6] in the decay of ^{80}Zr. Energies of states are given in keV. The isomeric state investigated in this work is marked by the thick line.

ating states that determine whether the population of an isomer relative to the ground state deviates from thermal equilibrium. A careful spectroscopic investigation [1,4,5] led to postulate that an 84 keV $E1$-transition feeds the isomeric state with energy 228.5 keV and half-life 4.7 s which is de-excited very probably by an $M3$-transition to the ground state of ^{80}Y. Very recently, the isomeric transition of 84 keV was observed in the decay of ^{80}Zr [6]. The adopted scheme of excitation energies of ^{80}Y populated in the decay of ^{80}Zr is shown in fig. 2.

The exact spin identification of isomeric states can be done by determining the multipolarity of isomeric transitions from measurements of internal conversion coefficients. A first attempt for such a measurement for the 228.5 keV transition in ^{80}Y has been performed very recently [7]. This experiment yielded an internal conversion coefficient of $\alpha_K = 0.47 \pm 0.15$. The relatively large error originates from the large energy loss of the emitted electrons due to deep implantation of reaction recoils and from background. The most probable transition multipolarity from this measurement is $M3$ [7].

For rp-process calculations, an unambiguous determination of the multipolarity of the 228.5 keV isomeric transition in ^{80}Y is needed. We therefore performed a new, independent spectroscopic investigation of ^{80}Y with the goal to verify and to improve the accuracy of the previous experimental determination of the internal conversion coefficient. For this experiment, we used the HIGISOL facility [8] which provides a mass-separated beam of nuclides and very thin implanted sources important for the measurement of low-energy electrons. For these measurements we used the electron magnetic transport spectrometer ELLI [9].

A $^{32}S^{7+}$ beam with an energy of 150 MeV from the isochronous cyclotron of the Jyväskylä University irradiated an enriched 2.7 mg/cm^2 ^{54}Fe target. The reaction products passing through a Havar window with thickness 2.2 mg/cm^2 were stopped in a helium gas cell. After extraction from the gas cell and acceleration to an energy of 40 keV, the ions were mass separated and deposited on a collector tape. To study the decay of the deposited activity, the ion beam was periodically swiched on and off. The typical time regime for this was (10 s+10 s) or (20 s+20 s). Since the electromagnetic mass separator transmits nuclides with the same isobaric mass value, it was important to suppress the nuclides of other elements in the $A = 80$ mass chain which have higher production yields than ^{80}Y, *e.g.*, ^{80}Sr [10]. To avoid this problem, we used the high probability of the HIGISOL system to produce selectively the oxide molecules when equipped with a SPIG (SextuPole rf Ion Guide) [11]. Thus, the ^{80}Sr-ions were observed predominantly in the monoatomic form at mass number $A = 80$, whereas ^{80}Y was produced mainly in the form $(YO)^+$ and can be seen at mass number $A = 96$. The ratio Y/Sr was 24 times higher for oxyde than for monoatom. The background at $A = 96$ was very small because of the suppression of the contribution from other elements. Nuclides with mass number $A = 96$ do not contribute because they are not produced in the reaction used.

The spectrometer ELLI which we used for measurements of conversion electrons, provides very low-background conditions. This broad-range high-transmition device consists of a two-coil magnetic transporter. The implantation area on the movable tape is located just at the first maximum of the magnetic field, while the Si(Li) conversion electron detector is placed in the focus at the second maximum. The point of deposition of reaction products on the tape was monitored by a LEGe-detector for low-energy γ-ray detection. This detector was installed outside the vacuum chamber of the spectrometer in close geometry with respect to the implantation area. The typical efficiency of the ELLI spectrometer was about 10% for electron energies around 250 keV.

For every event the amplitude and timing information from the detectors was stored in list mode for later analysis. To simplify the identification of the background peaks,

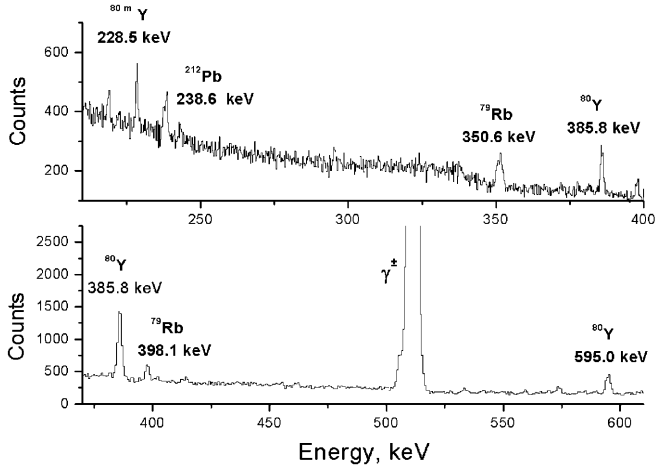

Fig. 3. γ-ray spectrum measured at the mass $A = 80$. The upper part shows the spectrum detected by the LEGe-detector, whereas the bottom part belongs to measurements with a 35%-efficiency germanium detector in coincidence with the thin plastic β-detector.

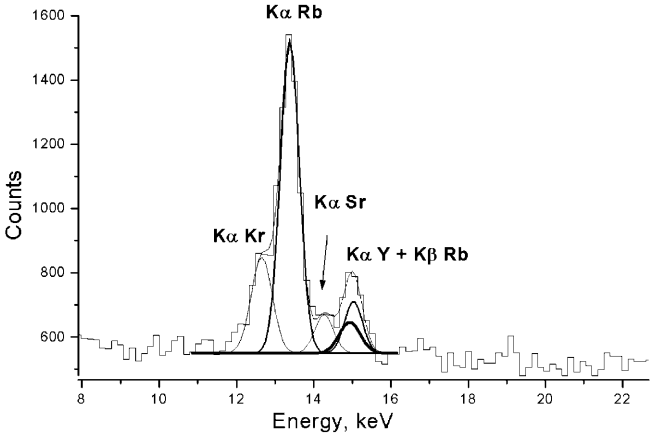

Fig. 4. Part of the X-ray spectrum measured for $A = 80$. The bold line, resulted from subtraction of the K_β-line of rubidium, belongs to K_α-line of Y.

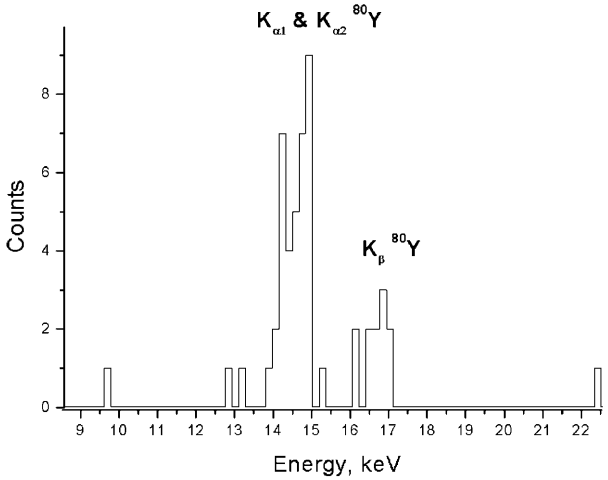

Fig. 5. Characteristic X-ray spectrum measured in coincidence with the conversion electron line for the 228.5 keV transition in ^{80}Y.

we performed measurements at neighboring mass numbers ($A = 81$ and 79 or 97 and 95). These spectra also allowed us to perform the internal calibration of the detectors. Thus, the electron detector efficiency calibration has been done by using the intense conversion electron lines in the decay of ^{81}Y, besides the external calibration with a ^{133}Ba source. The efficiency of the γ-detector in the energy range of the yttrium K_αX-line has been determined by using a standard ^{241}Am source. The low-energy γ-ray spectrum is shown in fig. 3. The upper part of this figure belongs to single spectrum, whereas the bottom part shows the γ-ray spectrum measured in coincidence with β-particles. We observed the γ-line with energy 228.5 keV in the single spectrum. However we did not observe this line in coincidence with β-particles that confirms the isomeric origin of 228.5 keV transition. A part of the characteristic X-ray spectrum is shown in fig. 4.

The intensity of K_α for yttrium (bold line in fig. 4) has been determined by subtracting the rubidium K_β-line contribution in the summed peak using the well-known K_α/K_β intensity ratio. Figure 5 presents the spectrum of X-rays in coincidence with the conversion line for the 228.5 keV transition observed at mass $A = 96$. This figure shows that the γ-peak with energy 228.5 keV can unambiguously be assigned to the de-excitation of the isomeric state in ^{80}Y.

The single-electron conversion spectrum is shown in fig. 6. The 211.7 keV line can unambiguously be assigned to K-shell conversion electrons from the transition of the isomeric state in ^{80}Y with an energy of 228.5 keV. The 176.1 keV peak in the spectrum originates from the K-conversion of the 190.5 keV isomeric transition in ^{81}Kr.

We used two ways to determine the internal conversion coefficient for the 228.5 keV isomeric transition in ^{80}Y. The first one is based on the absolute electron-to-gamma intensity ratio and the second one uses the $K\mathrm{X}/\gamma$ ratio measured by the same detector. The former method gave the value $\alpha_K = 0.51 \pm 0.09$, whereas the latter gave $\alpha_K = 0.48 \pm 0.13$. For the determination of the α_K-value from the X-ray spectrum we assumed that the KX-lines of yttrium originate only from the decay of the ^{80}Y isomeric state. This assumption is justified because the possible contribution from the decay of ^{80}Zr should be negligibly small because of the expected very small production yield of this nuclide. The values for the internal conversion coefficient obtained by the two different methods are in good agreement. The dominant source of the uncertainty in the internal conversion coefficients obtained are the electron and KX-ray statistics as well as Si(Li) and Ge-detector efficiences for electrons and X-rays, respectively. As these measurements have been performed with different detectors, we can average the two α_K values obtained. The average value is $\alpha_K = 0.50 \pm 0.07$. It is consistent with a $M3(+E4)$ multipolarity for the 228.5 keV isomeric transition (see fig. 7) and gives $I^\pi = 1^-$ spin-parity for this isomeric state.

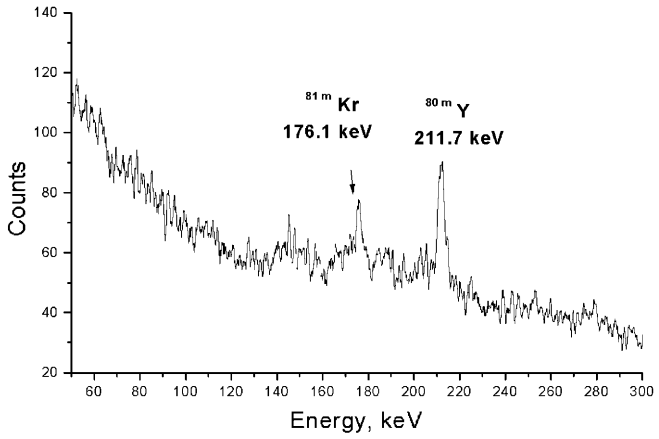

Fig. 6. Conversion electron spectrum measured by using the magnetic transporter system ELLI at mass $A = 96$.

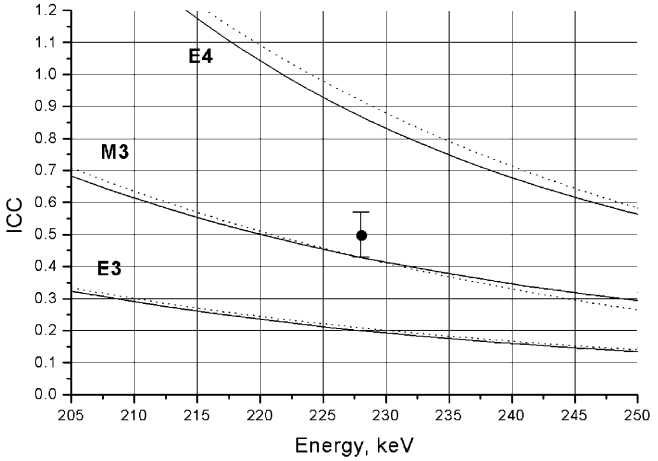

Fig. 7. The values of internal conversion coefficients of yttrium. The experimental value measured in this work is shown with error bar. The theoretical values are presented by lines, where the solid line stands for results taken from ref. [12] and the dotted line from ref. [13].

Figure 6 shows that there is no e-line belonging to the 84 keV transition. If this transition has an $E1$ character and is populated by the 228.5 keV transition, then we would expect a corresponding electron line with an energy of 67 keV and an intensity of 485 ± 75 counts. For an $M1$-transition the intensity should be 798 ± 123 counts and for other multipolarities we expect even higher intensities. However, from the spectrum pictured in fig. 6 we obtain an upper limit for the 67 keV line intensity of 120 counts. This result shows that the 84 keV transition is placed above the 228.5 keV state in the excitation spectrum of ^{80}Y. The information obtained in this work is in a good agreement with previous data [2–7] and confirms the spin-parity identification and order of isomeric states in ^{80}Y established so far. The half-life determined in this work for the 228.5 keV isomeric state is 5.0 ± 0.5 s which is in agreement with the value 4.7 ± 0.3 s, measured in ref. [2]. The weighted average value is 4.8 ± 0.3 s.

In the stellar plasma of an X-ray burst, ^{80m}Y is expected to be fully ionized. Then the de-excitation of the isomeric state by emission of a conversion electron is impossible. The half-life of the bare state ($T_{1/2,\mathrm{bare}}$) can be determined by

$$T_{1/2,\mathrm{bare}} = T_{1/2,\mathrm{neutral}} \times \left(\mathrm{br}_{\beta^+} + \frac{\mathrm{br}_{\mathrm{int}}}{1+\alpha} \right)^{-1},$$

where br_{β^+} and $\mathrm{br}_{\mathrm{int}}$ stand for branching ratios for β^+ and internal decays of the isomeric state, respectively; α means the internal conversion coefficient. The latter can be deduced from the measured value of α_K and the theoretical ratio $\alpha_K/\alpha = 0.867$ [12] for the 228.5 keV transition. Using the values $\mathrm{br}_{\beta^+} = 0.19 \pm 0.02$ and $\mathrm{br}_{\mathrm{int}} = 0.81 \pm 0.02$ from ref. [2] and $\alpha_K = 0.50 \pm 0.07$ measured in this work, as well as the weighted average value $T_{1/2,\mathrm{neutral}} = 4.8 \pm 0.3$ s, we find $T_{1/2,\mathrm{bare}} = 6.8 \pm 0.5$ s for the 228.5 keV isomer in stellar plasma conditions. The partial γ-decay half-life is 9.3 s and the partial β-decay half-life is 25 ± 4 s. The total bare lifetime of the ^{80}Y isomeric state is therefore comparable with typical rp-process time scales (10–100 s) [14]. In addition, the rp-process produces ^{80}Y exclusively in its isomeric state via β-decay of ^{80}Zr, and mediating higher-lying states that would provide a rapid link to the ground state via thermal excitations are not known. Because the lifetime of the isomer against proton capture is many orders of magnitude smaller than the decay lifetime during most of the rp-process, proton capture will predominantly occur on the ^{80}Y isomeric state, and not on the ground state as previously assumed. During freezeout we still expect a strong population of the isomeric state exceeding thermal equilibrium. Again, proton captures on the isomeric state will play an important role. Similarily, the ^{80}Y β-decay rate will at least in part be determined by the partial β-decay lifetime of the isomeric state. This clearly demonstrates the potential importance of isomeric states in the rp-process and makes ^{80}Y an ideal test case.

In conclusion, the HIGISOL facility has been used for production and separation of ^{80m}Y. Thin sources prepared on-line by implantation of a 40 keV mass-separated ion beam into a moveable tape have been used for measurements of electron conversion spectra. The electron magnetic transporter ELLI has been used to allow measurements under very clean background conditions. The transition with an energy of 228.5 keV and half-life of 5.0 ± 0.5 s was unambiguosly assigned to isomeric state de-excitation. The absence of other ^{80}Y conversion electron peaks in the spectra reliably identifies the 228.5 keV excited state as a first long-lived isomeric state. The measured value for the internal conversion coefficient $\alpha_K = 0.50 \pm 0.07$ confirms the $M3$ character of the transition and the 1^- identification for the state proposed previously. Whether the 228.5 keV isomeric state affects the overall lifetime of ^{80}Y, and therefore rp-process nucleosynthesis, depends on the extent that proton capture rates and β-decay rates of isomeric and ground state differ. Because of the similarity of the partial β-decay half-lives of the ^{80}Y

isomeric state (25±4 s) and the ground state (30.1±0.5 s), the impact of the isomeric state on the effective ^{80}Y β-decay lifetime will be a reduction by not more than 17±2% (for 100% population of the isomeric state). This work, together with previous work, provides the necessary data (excitation energies, spins and parities) for a recalculation of the proton capture rate on the ^{80}Y isomeric state. Such a calculation is currently underway and the results will be published elsewhere together with a quantitative analysis of the impact on X-ray burst models [15].

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