Low-Lying Excitations in the Odd-Odd Nucleus $^{154}$Eu

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The doubly odd nucleus $^{154}$Eu was produced during in-beam bombardments of a $^{154}$Sm target with $^3$He and deuteron beams at 27 and 10 MeV. The resulting gamma-rays were investigated using prompt and delayed gamma-gamma-coincidence equipment. The half-life of the isomeric $2^+$ level was determined as $2.2 \pm 0.1 \mu$s. The partial level scheme, including numerous previously unidentified excitations, can be divided into two separate groups of levels. The results provide evidence for the existence of a very regular ground band and two rather regular $K=3$ level structures, whose configurations are closely related to it. In addition, several rotational sequences built on the band heads with other $K$ values have been deduced. Our interpretation of the level scheme disagrees with the previous conclusion that the $N=91$ nucleus $^{154}$Eu might have a stable deformation only in its ground state configuration.

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1. Introduction

The nucleus $^{152}$Eu is the most studied [1] among the doubly odd nuclei in the light rare earth region. In the neighbouring nucleus $^{154}$Eu, the decay of the 47 min long-lived, $8^-$ isomer at 145 keV has been investigated in [2]. This together with the results of a previous $\gamma\gamma$-coincidence measurement in an $(n, \gamma)$ study [3] has provided a firm basis for later investigations. A more recent series of measurements with the $(n, \gamma)$- and $(d, p)$-reactions summarized in [4, 5] yielded a lot of additional information on individual low-energy excitations in $^{154}$Eu. In particular, the existence of several rotational structures has been suggested [5], but the interpretations are usually based at most only on two or three identified first states. This is, however, a rather small amount of information to use for constructing bands from various closely located candidates. The ground band is best known from the data of the $(p, p')$ reaction [6]. In the other $N=89$ or $N=91$ odd-odd nuclei only a few members of the ground band, together with a couple of level sequences populated with various $(HI, xn)$ reactions, are known so far [7, 8].

Another common feature of the odd-odd nuclei located in the $A=150$ mass region is the existence of low-lying isomeric states with lifetimes of a few tens of nanoseconds to a few microseconds. The spin-parity assignment, excitation energy and half-life of the two isomers for $^{154}$Eu within that time-scale are as follows: $2^+$, 68.2 keV, 2.2 $\mu$s and $4^+$, 100.9 keV, 55 ns. Despite the recent experimental progress, a common shortcoming is that the medium-spin range from about five to eight units of $\hbar$ is still almost untouched. In other words, according to present knowledge, it is not known how the yrast bands produced in some $(HI, xn)$-reaction are connected with the low-energy excitations. Therefore, to fill this gap in knowledge we started an extensive series of studies using light ion beams combined with various $\gamma\gamma$-coincidence arrangements.

The low-lying excitations were produced during in-beam experiments carried out by bombarding a $^{154}$Sm target with $^3$He and deuteron beams. Two different projectiles were also used in the delayed coincidence experiments, since it was thought that the former would favour excitations feeding the $ns$-isomers with a $K$ value of 4 and the latter favours...
the $\mu$-isomer with $K=1$. Four parameter delayed $\gamma\gamma$-coincidence measurements allow for the classification of the gamma rays into two separate groups associated with either one of the isomeric states above.

Almost all low-energy gamma rays connected with those isomers in previous papers [3, 4] have been identified in the present study. Thus the results of these experiments largely confirm the earlier data, but many other, new gamma rays were also included in our level schemes as well. For example, the prompt coincidence data undoubtedly indicate the existence of a very regular ground band populated up to the spin value of $10^-$. Placings of the first-time observed transitions as well as the spin assignments tentatively suggested are entirely based on the established levels [3-5]. The present half-lives of the $2^+$ and $8^-$ isomers are $T_{1/2}=(2.2\pm0.1)\mu$s and $T_{1/2}=(47.0\pm0.5)$ min, which is in good agreement with the data available in the literature [2, 3]. A detailed discussion with theoretical predictions on the neutron-proton configurations of the excitations will be presented in a forthcoming article [9].

2. Experimental Methods

In the rest of this paper we will refer to the delayed and prompt coincidence experiments by the letters $d$ and $p$ in parenthesis thus $(d)$, $(p)$. The deuteron beam will be represented by $D$.

A metallic self-supporting $^{154}$Sm target (purity 99%) was bombarded with the 27 MeV $^3$He and 10 MeV deuteron beams from the Jyväskylä cyclotron in $(d)$. In $(p)$ experiments the energy of the $^3$He projectiles was varied $22$ to $27$ MeV. Thus the excited states in $^{154}$Eu were produced through the $(^3$He, $p2n)$ and $(d, 2n)$ reactions. The natural pulsing of the cyclotron was utilized in all cases except for the delayed $^3$He measurements, for which an external fast pulsing system [10] was used.

The coincidence set-up consisted of two planar Ge detectors in close coincidence geometry with each other, these being $1.4\text{ cm}^3$ (FWHM 0.55 keV at 121.8 keV, detector 1) and $7\text{ cm}^3$ (0.6 keV, detector 2). They were well shielded to eliminate coincidence events arising from backscattered gamma rays, while the X-rays from the target were attenuated by proper absorbers. All coincidence data were collected and stored in a four or two parameter ($E_1, E_2, t_{12}, t_{2RF}$), ($E_1, t_{1RF}$) mode. Later the various events were preselected and sorted to isolate the desired two-dimensional coincidence space for each individual analysis. These steps were carried out as described in a previous report [11].

The time between the beam pulses restricted the time region available in the $^3$He $(d)$ experiment to $412$ ns, while the time condition of the coincident $\gamma$-rays was selected as $4\mu$s with an analog discriminator. The accidental coincidences due to the beam pulses during the data collecting periods were eliminated later by accepting nonprompt events alone. Prompt, unwanted events were excluded by requiring that the $t_{12}$ time region starts $30$ ns after the prompt peak. Transitions feeding the shorter-lived isomer were resolved with the aid of two other well-specified $t_{2RF}$ and $t_{12}$ time conditions. Corresponding time limitations were also applied to the deuteron data to construct a desired coincidence space.

Internal energy calibration was achieved with the aid of the most intense reference peaks appearing in the coincidence spectra from well-established reaction channels. A gamma ray singles spectrum, which includes peaks from those reactions, is represented in [11]. The complexity of that spectrum explains, why we were unable to determine any reliable intensities for individual gamma rays. The observed gamma-ray energies are given in the partial level schemes of Figs. 5 and 6. Their accuracy is estimated to be 0.1–0.2 keV depending on the relative intensity of each particular transition.

3. Coincidence Spectra

Figure 1 presents the spectra of the delayed gamma rays obtained from the $(d)$ $^3$He experiments. In both the largest peaks exist at 68 and 101 keV. In the right-hand part of the figure the counts of the Sm KX-rays have been divided by a factor of four. A similar pair of spectra is of course obtained from the $(d)$ deuteron. For later comparison, Fig. 2 shows a gross coinci-

![Fig. 1](image-url)