LEVELS IN ^{130}Ba FED FROM ^{130}La DECAY

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The level structure of ^{130}Ba was studied from the β^+-decay of ^{130}La. The gamma rays emitted in the decay were measured using a Ge(Li) detector. The ^{130}La isotope was produced in the ^{130}Ba(p, n) ^{130}La reaction at a proton energy of $E \simeq 9.5$ MeV. A $^{130}\text{La} \to {}^{130}$Ba decay scheme is proposed.

1. Introduction

The ^{130}Ba nucleus belongs to the class of transitional nuclei whose structure cannot be described by the rigid rotator or harmonic vibrator models. For example, in the case of ^{130}Ba the energy ratio of the first 4^+ state to the first 2^+ state is equal to 2.5, whereas from the rotator and vibrator models the values 3.33 and 2, respectively, are predicted. The properties of the ^{130}Ba nucleus were studied in a number of theoretical calculations [1], [2], [3], which suggest that this nucleus is deformed ($\beta_0 \neq 0$) but at the same time very soft to gamma deformation. This means that the collective potential energy $V(\beta, \gamma)$ depends weakly on the gamma deformation parameter. A model which may describe such a γ-unstable nucleus was originally forwarded by Wilets and Jean [4], and its extension is discussed in Ref. [5].

The level structure of ^{130}Ba has been hitherto studied by the following experimental methods:

1. "Classical" spectroscopy. This method was used for studying the β^+-decay of ^{130}La to ^{130}Ba by Gerschel *et al.* [6] and Abdul-Malek *et al.* [7]. The first study was carried out using the NaI(Tl) spectrometer, while in the second one a Ge(Li) detector was applied. However, the available spectroscopic information is very scanty, since only the two lowest excited states in ^{130}Ba were determined (*cf.* [7]).

2. In-beam gamma spectroscopy. In this method the levels in ^{130}Ba were excited in the (charged particle, xn) reaction, and the "prompt" gamma-rays emitted in the deexci-

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tation process were studied [8], [9], [10]. The quasi-rotational ground state band was populated up to a level with spin and parity $I^\pi = 10^+$ [9]. Besides, the first 2^+ state in ^{130}Ba was Coulomb excited and the $B(E2; 0^+ \rightarrow 2^+)$ value was determined [11], [12]. Also the electric quadrupole moment of the first excited state, Q_{2^+}, was measured [12] and its value was found to be $Q_{2^+} = -1.1$b.

3. Out-of-beam spectroscopy (conducted in the intervals between accelerator beam bursts). In these experiments the isomeric state with $E_{\text{excit}} = 2.47$ MeV and $I^\pi = 8^-$ or 9^- was populated [13], [14] in the (^{12}C, xn) reactions on ^{122,124}Sn. The gamma-rays and conversion electrons accompanying the decay of the isomeric state were studied, and the decay scheme determined.

In the two latter methods the (HI, xn) reactions were used, which was the reason for the high spin levels being strongly excited. Quite different levels can be populated in the radioactive decay of ^{130}La; the energy available in the β^+-decay being high ($Q_{EC} = 5.7$ MeV, *cf.* [15]). It can therefore be expected that in the ^{130}La decay more than two levels (as it was observed in Ref. [7]) can be fed, and thus, new information can be obtained. This was the reason why we undertook the study of the ^{130}La decay.

2. *Experimental*

The experiment was conducted on the 10 MeV proton linear accelerator [16] at the Institute of Nuclear Research at Świerk near Warsaw. The ^{130}La sources were produced in the ^{130}Ba(p, n) ^{130}La reaction. The energy of the proton beam was 9.5 MeV, the Q-value for the (p, n) reaction being equal to -6.5 MeV [15]. Targets of enriched ^{130}Ba were prepared from Ba Cl_2. This compound was chosen because of the relatively low and not disturbing (the ^{130}La identification) activation of the Cl isotopes in the 10 MeV proton flux. Ba Cl_2 was dissolved in redistilled water, some of the solution was placed on Al foil (*ca.* 6.9 mg.cm^{-2}) and the water was evaporated. Subsequently a heating procedure was applied (at a temperature of about 140°C) in which the crystallization water was removed. The targets then were covered with Al foil (*ca.* 6.9 mg.cm^{-2}) and enclosed for protection against humidity. The target thickness was about 5 mg.cm^{-2}. The isotopic contents of our targets were as follows: 14.4% — ^{130}Ba, 1.0% — ^{132}Ba, 4.3% — ^{134}Ba, 7.7% — ^{135}Ba, 8.0% — ^{136}Ba, 10.3% — ^{137}Ba, 54.3% — ^{138}Ba.

Targets were irradiated in the proton beam when the ^{130}La isotope was produced. After the activation was terminated, the gamma-rays were studied. The measurements were performed using a 30 cm^3 Ge(Li) detector with a resolution (FWHM) of 2.4 keV and 2.9 keV for $E_\gamma = 1$ MeV and $E_\gamma = 2$ MeV, respectively. For energy calibration and efficiency determination ^{56}Co [17] and ^{226}Ra [18] sources were used.

As it was already mentioned, our targets contained apart from ^{130}Ba other stable barium isotopes owing to which the problem of isotope identification may get complicated. Fortunately, all lantanum isotopes (with the exception of ^{136}La), which may be produced in our experiment, have half-lives differing significantly from those of ^{130}La. The half-life for ^{130}La decay is 8.7 m [19]. The contribution of ^{136}Ba (which decays with $T_{1/2} = 9.87$ m [20]) can easily be provided for, since:

1. This isotope decays mainly (in *ca.* 97%) to the ground state of the daughter nuclei, so the excited levels in ^{136}Ba are weakly populated and the gamma-lines, which accompany the ^{136}La decay, are not intense.

2. The energies and intensities of the gamma transitions accompanying the ^{136}La $\rightarrow$ ^{136}Ba decay are well known [21].

Measurements were performed of:

a) Gamma-spectra from the La $\rightarrow$ Ba decay.

b) The decay of the gamma-lines; this allowed us to identify the gamma transitions associated with the decay of ^{130}La,.

c) Gamma-rays from the La $\rightarrow$ Ba decay together with gamma-radiation from calibration sources (^{56}Co or ^{226}Ra); this allowed us to improve the quality of gamma energy determination.

3. Results and discussion

The spectrum of gamma-rays observed in ^{130}La decay is shown in Fig. 1. The energies and intensities of 28 gamma transitions following radioactive decay of ^{130}La are listed in Table I. The level scheme of ^{130}Ba was constructed basing on these data, taking also into account the information about low-lying levels available from the previous works [7], [14]. The proposed decay scheme of ^{130}La is presented in Fig. 2. Five gamma transitions with 3.2% total intensity are not included in the decay scheme. The energy available for electron-capture decay of ^{130}Ba was not measured in this work, it was taken from Ref. [15], where it was found to equal 5.7 MeV with an uncertainty of about 1 MeV. It should be emphasized that this value was not an experimental one but was obtained by extrapolation. This value was used for the log ft calculations where the f-value was taken from the tables of Gove and Martin [22].

All the beta transitions were found to be allowed or first forbidden non-unique ones. In the upper limits of the log ft values (which are connected with the uncertainties involved in the Q_{EC} value and with the position of the five gamma-transitions) the first forbidden unique type beta transition in most cases could not be excluded.

The spin of the first and the second excited states in ^{130}Ba (see Fig. 2) were assigned in Refs [12], [14]. According to our data these two levels are fed in the radioactive decay. The value of log ft $= 6.5$ suggest that the beta-transitions to the first and the second excited states ($I^\pi = 2^+$ and 4^+) have an allowed or first forbidden (non-unique) character [23]. This means that the ^{130}La ground state spin equals 3. The parity of this state could not be determined.

The level spins in ^{130}Ba were assigned on the basis of the log ft values and of the rules given by Raman and Gove [23]. In our case these data do not allow us to determine the parity. Some additional information was obtained when the gamma-transition probabilities were taken into consideration. This may be examined for the case of the 1477.5 keV level where the log ft value suggests the spins: 2, 3, 4. If we assume that the spin and parity are $I^\pi = 2^-$, then the electromagnetic transitions of energies $E_\gamma = 569$ keV and $E_\gamma = 576$ keV (see Fig. 2) have multipolarities M1 and M2, respectively. The M2 transition ought to be very weak as compared with the M1 transition, but this is in disagreement with the experimental results. This disagreement can be avoided by assuming $I^\pi = 2^+$. The log ft value confines the spin to 2, 3 and 4 for the 908.1 keV level. This state decays

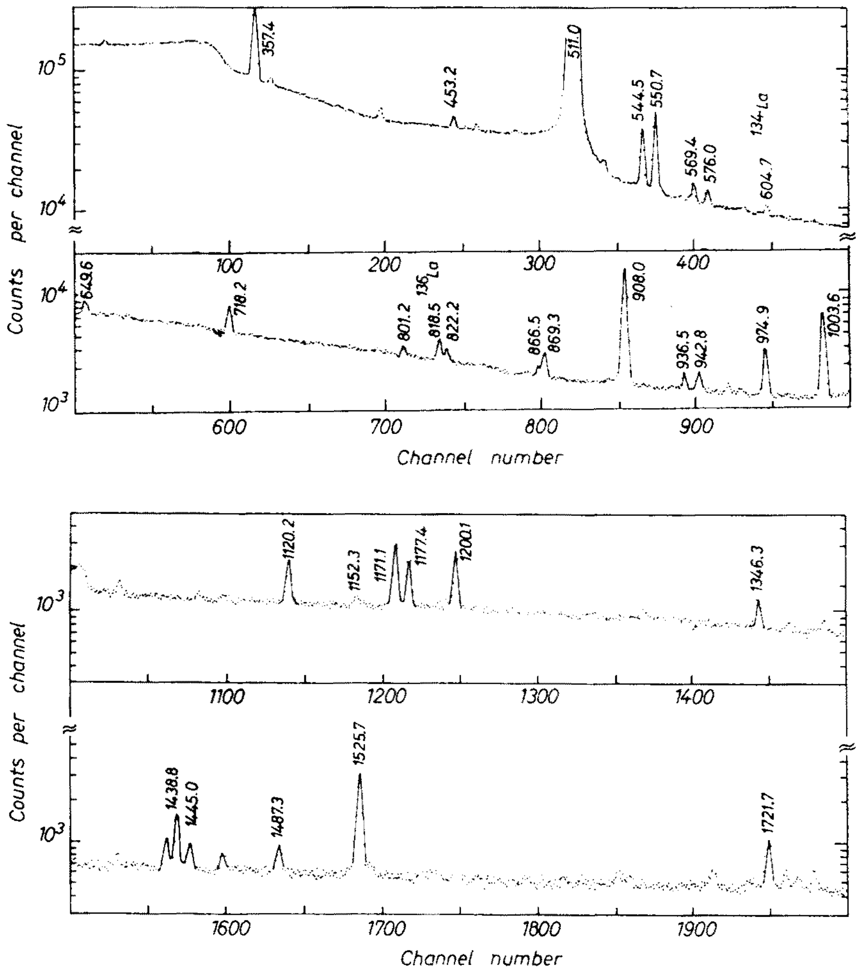

Fig. 1. Gamma-ray spectrum associated with La-decay. The spectrum was obtained using a 30 cm^3 Ge(Li) detector. A plexiglas absorber (thickness of 26 mm) was placed between the detector and the source to stop the positrons from the β^+-decay. The gamma-ray energy is given for all lines belonging to $^{130}La \rightarrow {}^{130}Ba$ decay

via gamma-emission to the 0^+ ground state and the 2^+ excited one. This restricts the spin and parity assignement to $I^\pi = 2^+$ which is in agreement with the tentative value given in Refs [10], [14].

As it was mentioned above, the microscopic calculations have shown that the potential energy surface $V(\beta, \gamma)$ is almost independent of the γ-deformation parameter. Such a result was obtained by the Bés-Szymański method [24] which was used by Arseniev *et al.* [1],

TABLE I

Energies and intensities of the gamma-transitions observed in the $^{130}La \rightarrow {}^{130}Ba$ decay. The lines whose assignement to ^{130}La decay is doubtful are marked with an asterisk. The energy error is less than 0.2 keV for all lines except where it is given otherwise

Gamma-ray energy (keV)	Gamma-ray intensity (arbitrary units)	Gamma-ray energy (keV)	Gamma-ray intensity (arbitrary units)
357.4	100	942.8	1.1
453.2*	4.9	974.9	3.7
544.5	18.8	1003.6	9.3
550.7	29.8	1120.2	2.2
569.4	2.9	1152.3*(0.3)	0.4
576.0	2.5	1171.1	4.3
649.6	1.7	1177.4	2.7
718.2	3.2	1200.1	3.3
801.2*	0.7	1346.3	1.1
822.2	0.9	1438.8	2.7
866.5(0.4)	0.5	1445.0	1.0
869.3	2.0	1487.3	0.9
908.0	20.3	1525.7	7.4
936.5	0.8	1721.7	2.0

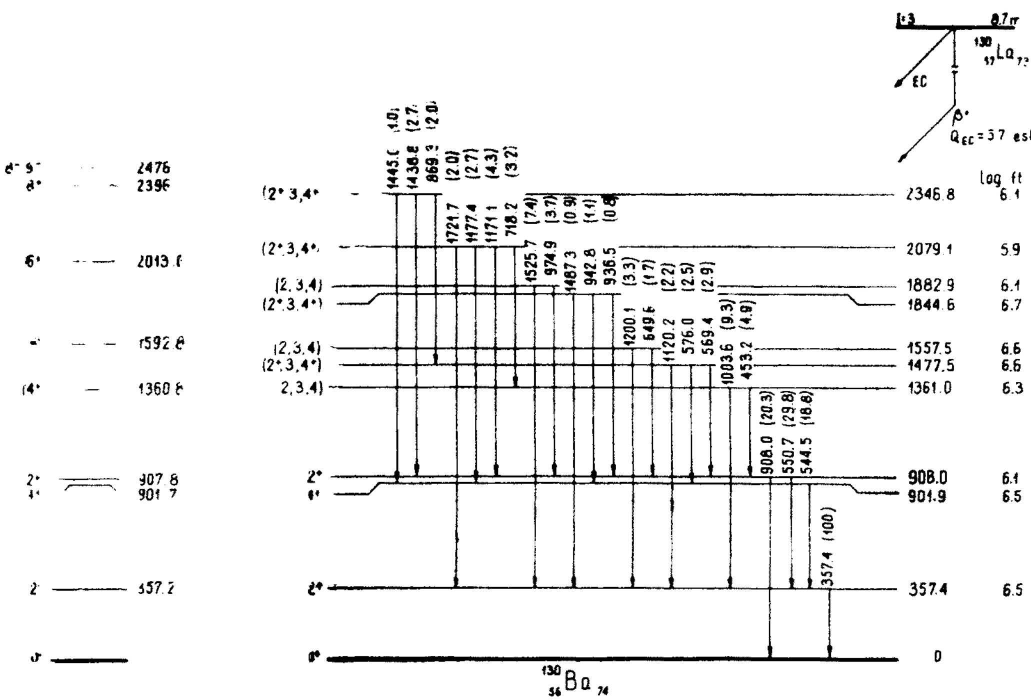

Fig. 2. Decay scheme of ^{130}La. The energy available for the electron-capture decay, Q_{EC}, was estimated in Ref. [15]. The half-life was determined in Ref. [19]. On the left-hand side the level scheme obtained from the (charged particle, xn) reaction is given (*cf.* [9], [14])

and also by the Strutinsky method [25] which was used by Ragnarsson [2] and Pomorski *et al.* [3]. This γ-independent potential and the almost γ-independent one were used in the simple collective models proposed by Arseniev *et al.* [26] and by Rohoziński *et al.* [5], respectively. The latter model was used by us for ^{130}Ba. When comparing the energies given by this model with the experimental values for levels with well defined spin and parity, a good fit was obtained (see Table II). However, we encountered difficulties in explaining some of the experimental data:

1. In the energy region near 1.5 MeV we observed three levels with energies 1361 keV, 1477 keV, 1557 keV and spins 2, 3 or 4. Using this model a multiplet with level spin and parity of 0^+, 3^+, 4^+ 6^+ should be expected in the mentioned energy region. We could not observe the 0^+ and 6^+ levels because of the spin of the ground state of ^{130}La which equals 3. The 6^+ level (E_{excit} = 1593 keV) was observed by Rotter *et al.* [13] and Ward *et al.* [14] in the (HI, xn) reaction. Among the three mentioned levels, two can have spin and parity 3^+ and 4^+ (as it is expected from the model). The presence of the third level is not predicted by this model, however it can be explained by assuming that it is a collective level with $I^\pi = 3^-$ (but there is no experimental evidence for this).

2. Using this model we could not obtain the reduced transition probability $B(E2; 2^+ \rightarrow 0^+)$ and the quadrupole moment Q_{2^+} values comparable with the experimental ones.

TABLE II

Experimental and calculated energy levels in ^{130}Ba. In the last column spins and parities of all possible levels belonging to the multiplets are given

I_{exp}	E_{exp}(keV)	E_{theory}(keV)	I_{theory}
2^+	357	363	2^+
2^+, 4^+	908, 902	895	2^+, 4^+
6^+	1593	1582	0^+, 3^+, 4^+, 6^+
8^+	2396	2408	2^+, 4^+, 5^+, 6^+, 8^+

Discrepancies between the experimental data and the predictions of the model were noticed by Rohoziński *et al.* [5] for other nuclei in the $50 < Z, N < 82$ region. These authors pointed out that one of the reasons for these discrepancies may be the dependence of the mass parameters on the γ-deformation.

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