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Letter

Identification of band structures in the ^{137}La nucleus

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Abstract. High-spin states of ^{137}La have been investigated with the reaction ^{130}Te(^{11}B, 4n) at a beam energy of 50 MeV. The level scheme of ^{137}La has been expanded with spin up to $33/2\hbar$. Several new bands have been found in this nucleus. A band crossing in the band based on the $17/2^-$ level has been observed at a rotational frequency of $\hbar\omega \sim 0.48$ MeV. From systematic comparison, this band crossing probably originates from the alignment of protons. One of the bands with strong $M1$ transitions is proposed as a collective oblate band ($\gamma \sim -60°$).

PACS. 23.20.Lv Gamma transitions and level energies – 21.10.Re Collective levels – 21.60.Ev Collective models

The nucleus ^{137}La lies in the $A = 135$ transitional region with the proton and neutron numbers approaching the closed shells at $Z = 50$ and $N = 82$. In this region, the nuclei have a small quadrupole deformation parameter β_2 and a soft γ-deformation. The proton Fermi surface lies in the lower $h_{11/2}$ subshell, whereas the neutron Fermi surface lies in the upper $h_{11/2}$ subshell. Thus, the rotational alignment of a pair of $h_{11/2}$ protons tends to drive the nucleus to a near prolate ($\gamma \sim 0°$) shape, while the rotational alignment of a pair of $h_{11/2}$ neutrons tends to drive the nucleus to a near oblate ($\gamma \sim -60°$) shape (Lund convention [1]). Therefore, the different quasiparticle configurations can drive a nucleus to different shapes and sometimes shape coexistence may be observed in a nucleus [2]. In previous publications, one of the most important structures in this region is the observation of collective oblate bands, for examples, in ^{131}La [3], ^{135}La [4] and ^{137}Ce [5]. On the other hand, in the neighboring La isotopes with $N < 80$, collective prolate band structures have been identified, and band crossing has been observed, such as in ^{135}La [4] and ^{136}La [6].

In the case of ^{137}La the neutron number is closer to the $N = 82$ shell. Therefore stronger single-particle properties are expected when compared to the neighboring $N < 80$ La isotopes. In order to systematically understand the nuclear-structure character, it is interesting to search for the collective band structure with higher spin states in ^{137}La nucleus. In previous works, some lower- and medium-spin levels in ^{137}La were reported by the ^{136}Ba(α, t) reaction [7] and by the ^{138}Ba(p, 2n) reaction [8], but no collective bands have been found. In this paper, we report on the experimental investigation of high-spin states and collective-band structures in ^{137}La.

High-spin states in ^{137}La were populated through the reaction ^{130}Te(^{11}B, 4n)^{137}La at a beam energy of 50 MeV. An isotopically enriched ^{130}Te target of thickness 1.6 mg/cm^2 was bombarded by the beam of ^{11}B ions accelerated by the HI-13 tandem accelerator at the China Institute of Atomic Energy (CIAE). The γ-γ coincidence measurement was carried out using an array of fourteen Compton-suppressed Ge detectors. The energy resolutions of the Ge detectors are between 1.8 and 2.2 keV at 1.333 MeV γ-ray energy. Approximately 1.8×10^8 coincidence events were collected, from which a γ-γ coincidence matrix was built. The relative efficiencies were calibrated with ^{152}Eu source. In order to determine the multipolarities of γ-ray transitions, the five detectors near 90° with respect to the beam axis were sorted against the other nine detectors at 45° (three), 55° (one), 125° (one) and 135° (four), to produce a two-dimensional angular-correlation matrix, from which it was possible to extract the average directional correlation of oriented state (DCO) intensity ratios. The γ-γ coincidence data were analyzed with the Radware software package [9].

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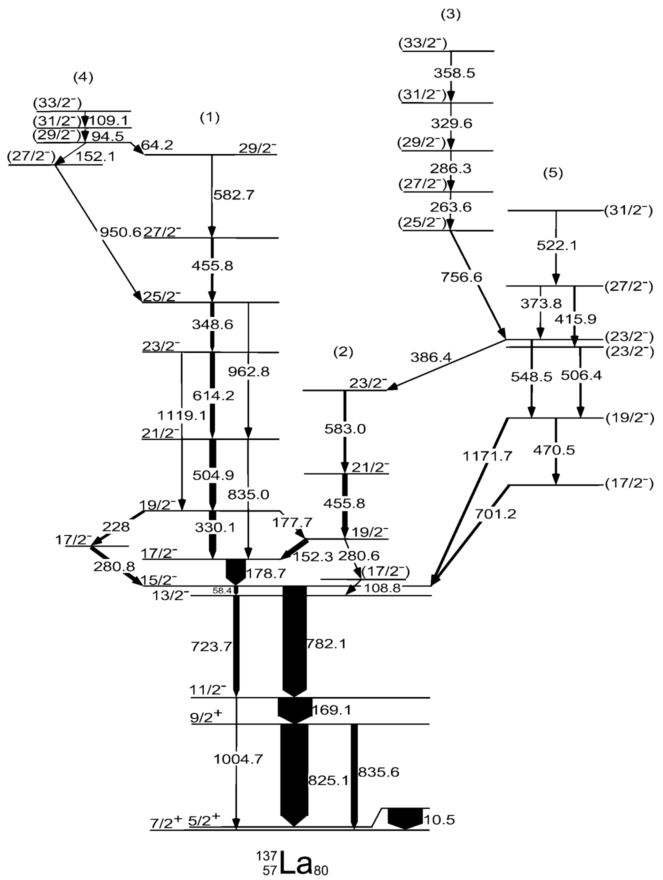

Fig. 1. Proposed level scheme of ^{137}La. The transition energies are given in keV.

The level scheme of ^{137}La obtained in the present work is shown in fig. 1. It was based on the γ-γ coincidence relationships, the relative transition intensities and the DCO ratio analysis. The transition intensities are represented by the width of the arrows. Some of the levels and transitions observed in ref. [8] were confirmed in the present work. All levels and transitions above the $15/2^-$ level, including 27 levels and 38 transitions, were newly identified in our work. Four collective bands observed are labeled on the top of the scheme. A cluster of levels labeled (5) in fig. 1 is complex and probably has single-particle property.

Some of the coincidence γ-ray spectra are shown in figs. 2 and 3. Figure 2(a) shows the spectrum obtained by gating on the 330.1 keV transition, where the transitions in band (1) are clearly seen and the transitions in band (4) can also be seen. Figure 2(b) shows the spectrum obtained by gating on the 152.3 keV transition, and the transitions in band (2) are clearly seen. Figure 3(a) and 3(b) show the transitions relative to bands (3) and (5). In all spectra, one can also see the corresponding coincidence γ-peaks between the lower-spin states. It is worth noticing that γ-peaks 455.8 and 583.0 keV of band (2) are overlapped with the γ-peaks 455.8 and 582.7 keV of band (1) respectively, so that it is more complex to analyze the structures of band (1) and band (2). Based on the analysis of the γ-γ coincidence relationships and the relative transition intensities, these overlapped peaks were successfully identified.

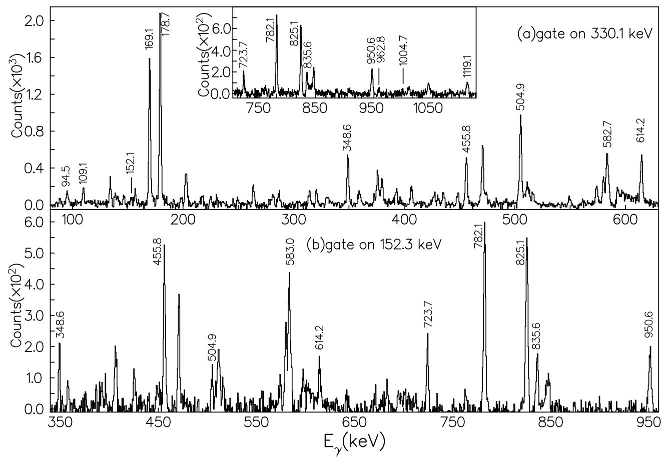

Fig. 2. Coincidence spectra by gating on (a) 330.1 keV and (b) 152.3 keV γ-transitions. The 152.3 keV transition is a doublet with the 152.1 keV of band (4).

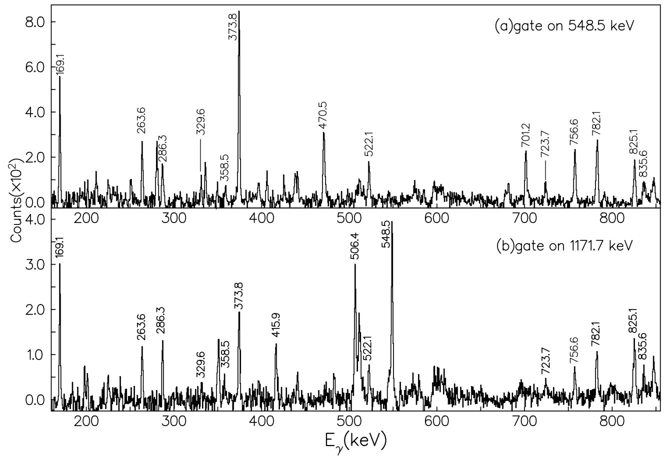

Fig. 3. Coincidence spectra by gating on (a) 548.5 keV and (b) 1171.7 keV γ-transitions.

Figure 4 shows the plot of DCO ratios for the transitions, included in the level scheme of ^{137}La, against γ-ray transition energies. As the statistics of DCO data is poorer than that of the total γ-γ coincidence matrix, the DCO values of some weak γ-peaks could not be determined. The DCO reference values for $\Delta I = 1$ and $\Delta I = 2$ transitions are 1.02 and 0.82, respectively. From the DCO ratios and the previous works [7,8], we assigned or tentatively assigned the spins and parities of the levels in ^{137}La, as shown in fig. 1.

The lowest levels in ^{137}La are mainly of proton $g_{7/2}$ and $d_{5/2}$ single-quasiparticle nature [8]. Figure 5 shows systematic comparison of the lower levels in La isotopes with those in the neighboring even-even Ba isotopes. The excited states of odd-A and even-even nuclei are normalized to the $11/2^-$ and 0^+ states in order to compare the level spacings in the odd nuclei with those in neighboring even nuclei. Indeed, the spacings in ^{133,135,137}La are closely similar to those of the ground band of the even-even Ba

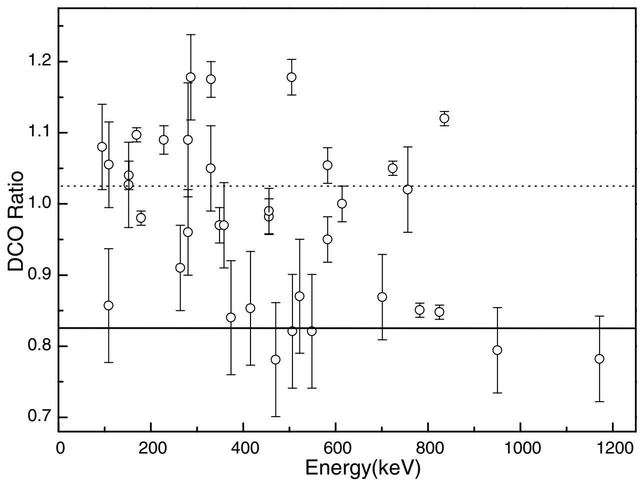

Fig. 4. DCO ratio *versus* γ-ray energies for several transitions in ^{137}La. The dashed line is drawn to indicate the reference value for $\Delta I = 1$ transitions. The solid line corresponds to the reference value for $\Delta I = 2$ transitions.

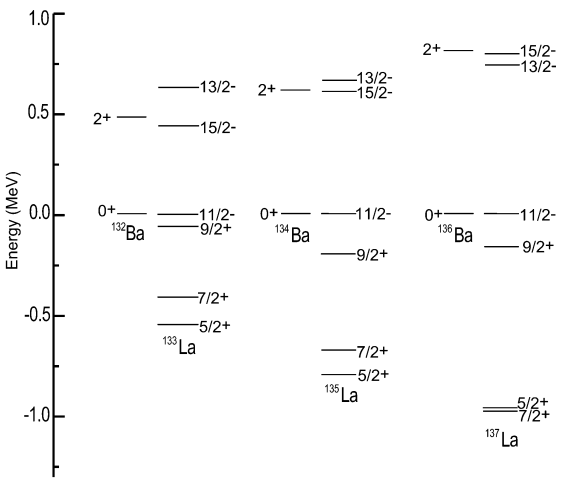

Fig. 5. The lower levels of La isotopes and the even-even Ba isotopes.

core. For the La isotopes, the single proton $h_{11/2}$ is probably the main component of the configuration of the $11/2^-$ states. The $13/2^-$ and $15/2^-$ states have been assigned to the $\pi h_{11/2} \otimes 2^+$ multiplet [8], which also were observed in the ^{139}Pr and ^{141}Pm [10]. The order of $13/2^-$ and $15/2^-$ levels does not change when going from ^{133}La to ^{135}La. But, the order of $13/2^-$ and $15/2^-$ levels changes from ^{135}La to ^{137}La.

Band (1) based on the $17/2^-$ state is constructed in our work with spin up to $29/2^-$. There are strong $M1$ transitions observed inside the band. Several $\Delta I = 2$ $E2$ transitions, such as 835.0, 962.8 and 1119.1 keV are also observed. The experimental $B(M1; I \to I-1)/B(E2; I \to I-2)$ values for $I = 21/2$, $23/2$ and $25/2$ are 19.5, 16.0 and 23.5 $(\mu_N/eb)^2$, respectively. It is expected that a $g_{7/2}$ proton or a $d_{5/2}$ proton must be associated with band (1). Coupling these protons to a high-K two-quasineutron configuration would yield a strongly coupled band such as band (1). Such high-K, sometimes isomeric, negative-parity two-quasineutron states are known in this mass region approaching $N = 82$. Indeed, in the ^{136}Ba core there is an isomeric $K^\pi = 7^-$ state based on the $\nu d_{3/2}^{-1} h_{11/2}^{-1}$ configuration [11,12]. Also there is a 364 ns isomeric $19/2^-$ state at 1869 keV in ^{137}La which does correspond to the $\pi g_{7/2} \otimes \nu d_{3/2}^{-1} h_{11/2}^{-1}$ configuration [8]. A band built on this state would not be seen in prompt coincidence. However, if we replace the $g_{7/2}$ proton with a $d_{5/2}$ proton, we would make a $\pi d_{5/2} \otimes \nu d_{3/2}^{-1} h_{11/2}^{-1}$ configuration which could then correspond to the $17/2^-$ state of band (1) at 1966 keV. This $17/2^-$ state is ~ 100 keV above the $19/2^-$ isomeric state, and in the same way the $5/2^+$ $(d_{5/2})$ state is ~ 10 keV above the $7/2^+$ $(g_{7/2})$ ground state. Therefore, band (1) is probably based on the $\pi d_{5/2} \otimes \nu d_{3/2}^{-1} h_{11/2}^{-1}$ configuration.

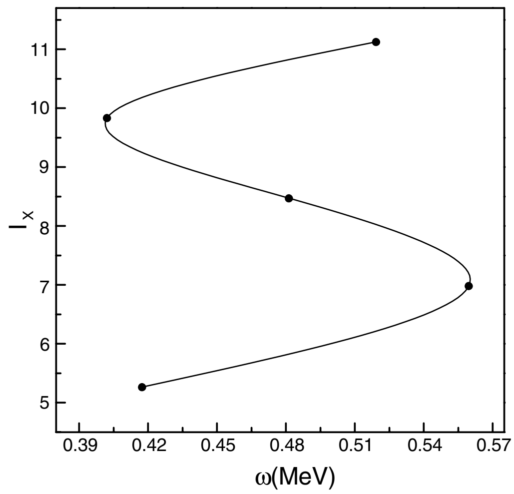

Fig. 6. Plot of the aligned spin *versus* the rotational frequency $(\hbar\omega)$ for band (1) in ^{137}La.

In fig. 6 we show the spin alignment I_x in band (1), calculated as a function of the rotational frequency $\hbar\omega$ from the usual formula $I_x = \sqrt{(I_a + 1/2)^2 - K^2}$, where $I_a = (I_i + I_f)/2$, $\hbar\omega = (E_i - E_f)/2$ and $K = 17/2$. One can see that a band crossing (backbending) occurs at $\hbar\omega \sim 0.48$ MeV. In ^{137}La, the effects related to the soft energy surface and to the configuration-dependent deformation become more evident when approaching the shell closure at $Z = 50$ and $N = 82$. In the neighboring odd-A nuclei ^{135}La [4], ^{137}Pr [13] and ^{141}Eu [15], the similar band crossings have been found, which are due to the alignment of a pair of $h_{11/2}$ protons. Based on the systematic comparison with the neighboring nuclei, we propose that the observed band crossing of band (1) in ^{137}La probably originates from the alignment of protons.

Band (3) has strong $\Delta I = 1$ dipole transitions and no $E2$ crossover transitions are observed. The limit $B(M1; \Delta I = 1)/B(E2; \Delta I = 2)$ values in the band can be estimated with greater than 12 $(\mu_N/eb)^2$. Based on a systematic comparison with the neighboring nuclei, for example, ^{135}La [4], ^{137}Pr [13], ^{139}Pm [14] and ^{141}Eu [15], we believe that the collective band should belong to a collective rotational oblate band built on a multiquasiparticle configuration with $\gamma \sim -60°$. Cranked shell model calculations have been carried out to understand the different shape driving effects of protons and neutrons in this region [2,3]. They show that the alignment of a pair of $h_{11/2}$ protons favors a prolate shape ($\gamma \sim 0°$) and the alignment of a pair of $h_{11/2}$ neutrons favors an oblate shape ($\gamma \sim -60°$). The oblate bands in this region exhibit some distinct properties: a) much stronger $\Delta I = 1$ transitions relative to the $\Delta I = 2$ transitions inside the band, b) no signature splitting occuring, and c) different moments of inertia from those of prolate bands. As discussed in refs. [2,3], for the oblate shape ($\gamma \sim -60°$), high-Ω $h_{11/2}$ protons and low-Ω $h_{11/2}$ neutrons are near the Fermi surface. Such high-Ω $h_{11/2}$ protons enhance the $B(M1)$ transition rates within the band. Band (3) observed in ^{137}La shows such characteristics. As the band head energy of band (3) is much higher than that in band (1), band (3) may belong to a five-quasiparticle band. The possible configuration can be assigned as $\pi g_{7/2}d_{5/2}h_{11/2} \otimes (\nu h_{11/2})^2$. Since for band (3) a configuration based on $\pi g_{7/2}d_{5/2}h_{11/2}$ coupled to $(\nu h_{11/2})^2$ is suggested, the strong $M1$ transition rates will be due to the high-Ω $h_{11/2}$ proton.

Although the large $B(M1)/B(E2)$ ratio is one of the most important properties of an oblate band, sometime the strong $B(M1)$ transition could be observed in a prolate quasiparticle band also, such as, in ^{100,102}Zr [16]. The $B(M1)/B(E2)$ ratios in ^{137}La are found to be similar in bands (1) and (3), but band (1) might have a different shape from band (3). In band (1), the signature splitting appears before the band crossing, but no signature splitting happens in band (3). The kinematic moments of inertia ($J^{(1)}$) are different in both bands. The average values are $\sim 26\ \hbar^2$/MeV before the band crossing and $\sim 30\ \hbar^2$/MeV after that in band (1), and $\sim 50\ \hbar^2$/MeV in band (3), respectively. Thus, one can see that the $J^{(1)}$ value in band (3) is much higher than that in band (1). So we assume that band (1) might have a prolate shape with some γ-degrees of freedom. After the band crossing, band (1) might have more triaxiality with γ toward $+30°$ caused by the alignment of a pair of protons, as discussed in refs. [2,3].

Band (2) might be based on a three-quasiparticle configuration. Band (4) should have a multi-quasiparticle configuration. Assigning their configurations needs more works.

In conclusion, the high-spin structure of the ^{137}La nucleus has been studied. Four new bands and one new level sequence have been established in this nucleus. A band crossing in the band based on the $17/2^-$ level has been observed. It is proposed that the alignment of protons is responsible for the band crossing. A collective oblate band has been observed and it probably originates from the five-quasiparticle configuration.

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