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Communications

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Odd parity levels in ^{133}La and the particle-plus-triaxial-rotor model*

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Odd parity levels in ^{133}La are studied by β decay of mass separated 5.4-h ^{133}Ce. Good agreement between experiment and theory is found for level energies and transition probability ratios when the particle-plus-triaxial-rotor model is used.

[RADIOACTIVITY ^{133}Ce; measured $E\gamma$, $I\gamma$, I_{ce}; deduced logft. ^{133}La deduced levels, J, π, ICC, Λ. Enriched targets, mass separation, Ge(Li) and Si(Li) detectors.]

The study of odd-mass lanthanum nuclei has revealed the importance of deformation in characterizing negative parity levels in certain neutron deficient nuclei with $A \approx 135$. Leigh *et al.*[1] used the (HI, $Xn\gamma$) reaction to populate an yrast band with spins of $\frac{11}{2}$, $\frac{15}{2}$, $\frac{19}{2}$, etc., built on the $h_{11/2}$ single proton state in the light odd-mass lanthanum nuclei. They observed stretched $E2$ γ-ray cascades having energies very close to those occurring in the ground band of the even-even barium core nuclei. Leigh *et al.* showed that the level energies of the yrast bands and the stretched $E2$ nature of the observed transitions were consistent with a particle-plus-rotor coupling scheme with a prolate deformation of $0.1 < \beta < 0.3$.[2-4]

The model proposed by Leigh *et al.* assumed symmetric deformation. However, calculation of deformation parameters from the 2_1^+, 2_2^+, and 4_1^+ levels of neighboring core nuclei result in a nonzero γ deformation parameter, suggesting that the nuclear core may have a triaxial shape. Theoretical calculations with the particle-plus-asymmetric-rotor model in this mass region have made predictions of energy level systematics and transition characteristics.[5,6] In particular, the asymmetric-rotor model predicts a lowering in energy of unfavored and low-spin levels compared with the yrast levels as the γ deformation increases from 0° to 30°.[5]

To date there have been few, if any, experimental data in this mass region to test the triaxial model's predictions on the low-spin levels and their properties. A comparison of the reduced transition probabilities for the $\frac{19}{2}^- \to \frac{15}{2}^-$ and $\frac{15}{2}^- \to \frac{11}{2}^-$ transitions in ^{129,131}La are quantitatively understood using a model that couples a rotation-aligned $h_{11/2}$ proton to a triaxial core.[7] In a recent study of ^{137}Nd levels,[8] the experimental energies of the lower-spin states were not in quantitative agreement with predictions of a particle-plus-symmetric-rotor model. Nowicki *et al.* suggested γ deformation may be necessary to account for the ^{137}Nd experimental results.

This study of γ rays which follow ^{133}Ce decay, and depopulate excited states in ^{133}La, provides a test of the particle-plus-asymmetric-rotor model in predicting the level characteristics of both low-spin and unfavored states, and in predicting the transition probability ratios from these levels.

Sources of 5.4-h ^{133}Ce for this experiment were made by the (α, xn) reaction on $BaCO_3$ targets. Cerium was separated chemically from the target material and mass separated onto aluminum foil to provide radioactive sources. A lanthanum-cerium chemical separation of one mass separated source, and subsequent counting, provided positive identification of γ rays following ^{133}Ce decay and ^{133}La decay. γ-ray singles counting, conversion electron counting, and a γ-γ-coincidence experiment were performed to study ^{133}Ce decay. Conversion electron data for many transitions in ^{133}La were made available for the first time by use of a trochoid conversion electron spectrometer, which eliminated the positron background from ^{133}Ce decay.

The portion of the ^{133}La level scheme pertinent to this discussion is shown in Fig. 1; an extensive level scheme has been developed for ^{133}La and will be published elsewhere. Included in the figure are relative photon intensities, β decay intensities to

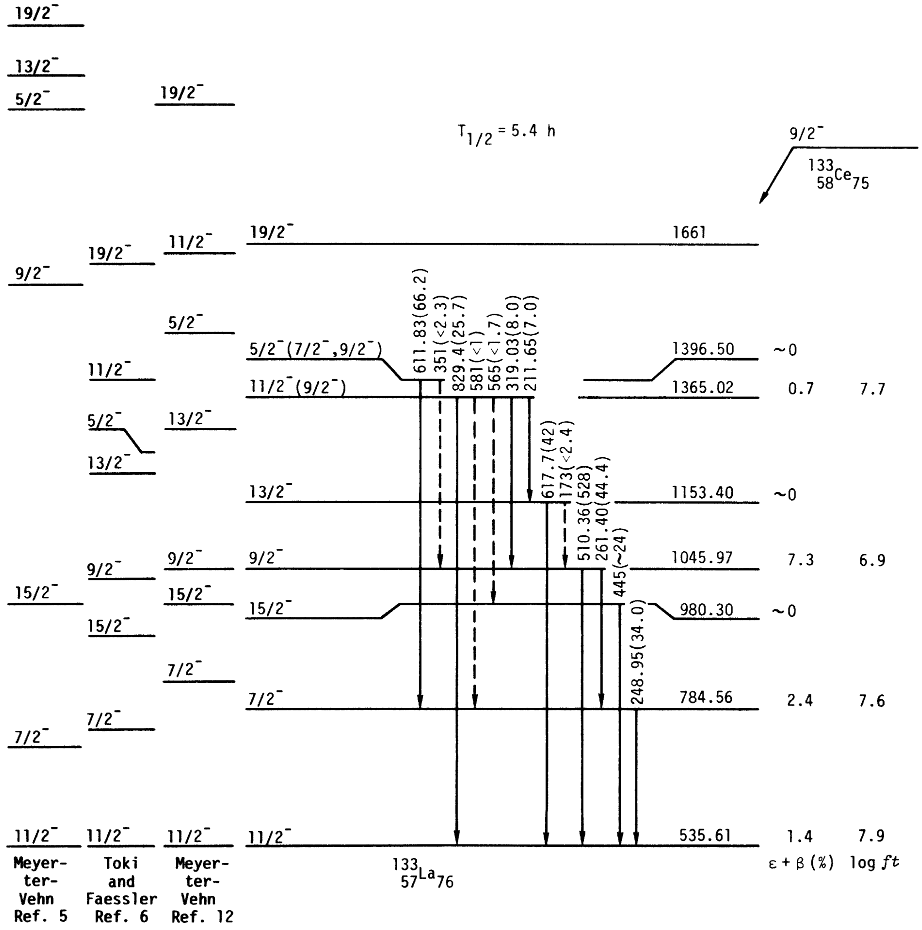

FIG. 1. Shown on the right are the low-lying negative parity levels deduced in this experiment. Included is the $\frac{19}{2}^-$ level deduced by Leigh *et al.* On the left are calculations by Meyer-ter-Vehn using a particle-plus-symmetric rigid-rotor model (Ref. 5), Toki and Faessler using a particle-plus-triaxial-rotor model with a VMI treatment of the core (Ref. 6), and Meyer-ter-Vehn using a particle-plus-triaxial rigid-rotor model with $\gamma = 24°$ (Ref. 12). (*Nota bene:* the second $\frac{11}{2}^-$ level predicted by the particle-plus-symmetric rigid-rotor model (Ref. 5) is at approximately 2870 keV, well above the $\frac{19}{2}^-$ level.)

the excited levels, and log*ft* values. Table I summarizes the experimental conversion electron intensities and deduced transition multipolarities for selected transitions.

The spins of the ^{133}La ground state and the 5.4-h isomer of ^{133}Ce are $\frac{5}{2}$ and $\frac{9}{2}$, respectively.[9,10] Allowed β decay to the $\frac{3}{2}^+$ 12.33-keV level in ^{133}Ba requires the ^{133}La ground state to have positive parity. From the Nilsson diagrams the $\frac{9}{2}$, 5.4-h isomer of ^{133}Ce has negative parity. The spins and parities of levels at 130.81, 477.24, and 535.61 keV are established to be $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{11}{2}^-$, respectively, from the conversion data of Gerschel[11] and the reaction results of Nakai *et al.*[3]

From the experimentally determined conversion coefficients, the log*ft* values, and the observed transitions, we have determined the spins and parities of the levels shown in Fig. 1. The evidence supporting these J^π values is summarized below:

784.56-keV level. The 784.54-keV ground state transition is $E1$ and the log*ft* value for this level is 7.6, requiring $J^\pi = \frac{7}{2}^-$ for this level.

980.0-keV level. This is the $\frac{15}{2}^-$ level observed by Leigh *et al.* and populated in this β decay study.

1045.97-keV level. The log*ft* value of 6.9, the $M1$ 510-keV transition to the 535.61-keV level, and the observation of a transition to the 130.81-keV level require J^π to be $\frac{9}{2}^-$.

1153.40-keV level. The K conversion coefficient of the 617.7-keV transition is consistent with that of an $M1$ transition though precise determination of this conversion coefficient is difficult because of interference from ^{133}La decay. Because the β decay branch deduced for this level is consistent with zero and the level decays only to the $\frac{11}{2}^-$ 535.61-keV level, we propose that this level has

TABLE I. Relative conversion electron intensities and deduced conversion coefficients of selected transitions in ^{133}La.

$E\gamma$	I_k (rel)	α_k [a] ($\times 10^3$)	Λ
477.22(4) [b]	1000(36) [c]	9.82 [d]	$E2$
510.36(7)	643(35)	12.9(12)	$M1$(<3%$E2$)
611.83(6)	45.0(3.7)	7.2(8)	$M1$(<48%$E2$)
617.7(3)	≈25 [e]	≈6.4	($M1$)
784.55(8) [b]	38(3)	1.6(2)	$E1$ (5 ± 3%$M2$)
829.42(15)	7.5(8)	3.1(4)	$M1$(47 ± 34%$E2$)

[a] See Fig. 1 for photon intensities except $I\gamma(475+477) = 1081$, $I\gamma(475) = 81$, and $I\gamma(784) = 246$.

[b] The 477-keV level and 784-keV level to γ-ray singles transitions, respectively.

[c] Includes the 475-keV γ ray.

[d] Data normalized to this conversion coefficient. α_k is 3.4% uncertain if the 475-keV γ ray is pure $M1$. This uncertainty is included in calculated conversion coefficients.

[e] Corrected for contributions from ^{133}La decay.

$J^\pi = \frac{13}{2}^-$.

1365.02-keV level. The logft value of 7.7 and the $M1$ 829.4-keV transition to the $\frac{11}{2}^-$ 535.61-keV level restrict J to $\frac{9}{2}^-$ or $\frac{11}{2}^-$. Because there is a transition to the $\frac{9}{2}^+$ 477.22-keV level, but no detectable transition to the $\frac{7}{2}^+$ 130.81-keV level, the $\frac{11}{2}^-$ assignment is favored.

1396.50-keV level. The $M1$ 611.83-keV transition limits J^π to $\frac{5}{2}^-$, $\frac{7}{2}^-$, or $\frac{9}{2}^-$. Because the β decay branch to this level is consistent with zero, we propose $J^\pi = \frac{5}{2}^-$.

1661-keV level. This level is observed by Leigh *et al.* and has $J^\pi = \frac{19}{2}^-$.

In addition to the experimental level scheme, Fig. 1 shows the level energies calculated by Meyer-ter-Vehn[12] as well as Toki and Faessler.[6] Meyer-ter-Vehn used a triaxial rigid-core model and determined the deformation parameters from the energies of the 2_1^+, 2_2^+, and 4_1^+ levels of the neighboring even mass core nuclei. The Fermi energy was adjusted to reproduce the $\frac{9}{2}^-$-$\frac{11}{2}^-$ separation. Toki and Faessler determined the deformation parameters in the same manner as Meyer-ter-Vehn. However, they used an asymmetric core with a variable moment of inertia (VMI). Both calculations reproduce the systematics of the observed levels well; Toki and Faessler obtain a closer quantitative agreement with the yrast levels as a result of their VMI treatment of the core.

The energy level predictions of a calculation using parameters similar to those in the present work but with a symmetric core ($\gamma = 0°$)[5] are also shown in Fig. 1. For $\beta = 0.20$, the $\frac{11}{2}_2$ level rises rapidly relative to the $\frac{11}{2}_1$ level and lies substantially above the $\frac{19}{2}_1$ level. Experimentally, the $\frac{11}{2}_2$ level occurs approximately midway between the $\frac{15}{2}_1$ and $\frac{19}{2}_1$ levels. Similarly, the $\frac{13}{2}_1$ level rises and is at approximately the same energy as the $\frac{19}{2}_1$ level when the symmetric prolate core is used. However, the $\frac{13}{2}_1$ level is found experimentally to be nearer the $\frac{15}{2}_1$ level than the $\frac{19}{2}_1$ level. Thus, the experimental levels are better reproduced by the triaxial-core model than the symmetric core model.

Table II summarizes a comparison of experimental and theoretical[12] transition probability ratios. The agreement between experiment and theory for these ratios is within a factor of 2 to 3. In cases where only limits can be determined experimentally, they are consistent with the theoretical values. An assignment of $\frac{9}{2}^-$ to the 1365-keV level and $\frac{7}{2}^-$ or $\frac{9}{2}^-$ to the 1396-keV level result in poor agreement between the calculated and observed ratios.

In summary, the present study of ^{133}La levels provide a significant test of the predictions of a particle-plus-asymmetric-rotor model. It is seen that the level systematics found experimentally are reproduced by such a model and quantitative agreement on level energies is obtained when core softness is taken into account. A symmetric core mod-

TABLE II. A comparison of experimental transition probability ratios and theoretical transition probability ratios.

Level	Ratio	Theory	Expt.
1045($\frac{9}{2}_1$)	$\frac{\frac{9}{2}_1 \to \frac{11}{2}_1}{\frac{9}{2}_1 \to \frac{7}{2}_1}$	4.7	11.3
1153($\frac{13}{2}_1$)	$\frac{\frac{13}{2}_1 \to \frac{11}{2}_1}{\frac{13}{2}_1 \to \frac{15}{2}_1}$	24.3	>14.7
1365($\frac{11}{2}_2$)	$\frac{\frac{11}{2}_2 \to \frac{7}{2}_1}{\frac{11}{2}_2 \to \frac{13}{2}_1}$	0.078	<0.16
	$\frac{\frac{11}{2}_2 \to \frac{9}{2}_1}{\frac{11}{2}_2 \to \frac{13}{2}_1}$	2.3	1.1
	$\frac{\frac{11}{2}_2 \to \frac{11}{2}_1}{\frac{11}{2}_2 \to \frac{13}{2}_1}$	1.6	3.7
	$\frac{\frac{11}{2}_2 \to \frac{15}{2}_1}{\frac{11}{2}_2 \to \frac{13}{2}_1}$	0.034	<0.24
1396($\frac{5}{2}_1$)	$\frac{\frac{5}{2}_1 \to \frac{7}{2}_1}{\frac{5}{2}_1 \to \frac{9}{2}_1}$	33	>28

el fails to reproduce the ordering and spacing of levels between the $\frac{15}{2}_1$ and $\frac{19}{2}_1$ levels in ^{133}La. In addition, the triaxial model predictions of transition probability ratios are in agreement with those determined experimentally. Thus, the particle-plus-asymmetric-rotor model provides a quantitative explanation for the features of the odd parity ^{133}La levels presented in this study.

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