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Evidence for near instability against gamma deformation in ^{128}Ba†

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The decay of 5.2-min ^{128}La to levels in ^{128}Ba has been investigated by γ-ray and conversion-electron spectroscopy. Of 78 γ rays assigned to the decay, 69 have been placed in a decay scheme consisting of 31 excited states. The ^{128}La ground state is probably 5^- and is interpreted as the $(\nu\,\frac{7}{2}^-[523]+\pi\,\frac{3}{2}^+[411])$ configuration. EC + β^+ decays with logft values in the allowed range to states at 2425.5 and 2878.3 keV are explained by $(\nu\,\frac{7}{2}^-[523]+\nu\,\frac{1}{2}^+[411])_{4-}$ and $(\nu\,\frac{7}{2}^-[523]+\nu\,\frac{3}{2}^+[402])_{5-}$ configurations, respectively. A quasi-γ band is proposed with levels at 884.5 keV (2^+), 1324.5 keV (3^+), 1372.4 keV (4^+), and 1931.4 keV (5^+). A state at 1939.4 keV is possibly the 6^+ band member. The properties of ^{128}Ba were calculated using the microscopic boson-expansion code of Kishimoto and Tamura and found to be in rather good agreement with experiment. The small experimentally observed splitting (48 keV) between the 3_γ and 4_γ states is a signature of γ instability. The prolate-oblate difference, consistent with the experimental data, is estimated to be 0.5 MeV, a value in good agreement with potential-surface calculations.

[RADIOACTIVITY ^{128}La [from ^{118}Sn(^{14}N, $4n$)], measured $T_{1/2}$, E_γ, I_γ, I_{ce}, γ-γ coin; deduced logft. ^{128}Ba deduced levels, ICC, J, π. Enriched target, Ge(Li) and Si(Li) detectors.]

I. INTRODUCTION

The neutron-deficient La and Ba nuclei lie in a proposed region of deformation.[1] While considerable theoretical interest has been shown in nuclei with $Z>54$ and $N<78$, detailed experimental structure studies have been largely limited to in-beam investigations, principally due to the difficulties involved in decay studies with nuclei with relatively short half-lives. While ground-state-band (gsb) and high-spin phenomena have been investigated to some extent, the properties of low-lying lower-spin states in this region are less well known. Such knowledge, however, is essential to test recent microscopic theoretical calculations[2] which have suggested that some of the lighter Ba and Ce nuclei should have very small differences between the prolate and oblate well depths and, consequently, could be nearly γ-unstable nuclei. Although a model for a γ-unstable nucleus was originally proposed by Wilets and Jean and consequently discussed by others,[3] experimental evidence for a nucleus of this type has not been found. With this background in mind, an investigation was undertaken of the decay of ^{128}La to levels in ^{128}Ba—a nucleus which according to theoretical predictions[2] should be soft to γ deformation and should therefore have a high degree of γ instability.

A previous study[4] of the ^{128}La decay obtained γ-ray singles and γ-β^+ coincidence data but provided minimal information on the level structure in ^{128}Ba. A recent in-beam investigation[5] has established the gsb to spin 12^+ and a possible negative-parity odd-spin side band between spins 7 and 15. The mean lifetime of the 2^+ first-excited state has been measured[6] with the recoil-distance Doppler-shift method and the calculated $B(E2)$ value found to equal 83 ± 18 single particle units. This result confirms the collective character of this transition and the transitional character of ^{128}Ba, and lends some supporting evidence for the results of the microscopic calculations.[2]

II. EXPERIMENTAL PROCEDURES AND RESULTS

The ^{128}La activity was produced by the ^{118}Sn(^{14}N, $4n$)^{128}La reaction. The target consisted of ^{118}Sn in the oxide form bound with adhesive spray to a 1.7-mg/cm^2 Al backing. This backing foil and a 3.4-mg/cm^2 chamber sealing foil reduced the energy of the extracted 90- and 100-MeV ^{14}N beams to 78 and 90 MeV, respectively.

The He-jet technique[7] was used to transport the recoiling product nuclei approximately 35 m from the bombardment site to a counting area where the activity was collected on Mylar or acetate tape. Sources prepared in this fashion were automatically counted in succession for fixed time intervals ranging from 10 sec/source to 5 min/source in various experiments. From these spectra, γ rays belonging to activities with different half-lives could be readily identified. Impurity identification was further simplified by direct production of the ^{127}La and ^{129}La activities using ^{117}Sn and ^{119}Sn targets.

γ-ray spectra were taken with 35-cm^3, 40-cm^3, and 65-cm^3 Ge(Li) detectors with resolutions full width at half maximum (FWHM) measured to be 1.78, 2.25, and 2.35 keV, respectively, at 1332 keV. The energies of the stronger γ-ray transitions were obtained from simultaneous calibration against known standards while those of weaker lines were obtained by interpolating between the stronger ^{128}La transitions. A typical ^{128}La γ-ray spectrum obtained by counting 600 separate sources for 90 sec each with the 65-cm^3 Ge(Li) detector is shown in Fig. 1.

An internal-conversion-electron spectrum was obtained using a 3-mm × 100-mm^2 Si(Li) detector with 2.2-keV resolution (FWHM) for the 1064 K conversion line in ^{207}Bi. The electrons were counted through a 900-μg/cm^2 aluminized Mylar foil which separated the relatively poor vacuum on the He-jet source collection side (~1 Torr) from the high vacuum in the detector chamber (10^{-6}–10^{-7} Torr). The details of the application of the He-jet technique to conversion-electron spectroscopy have previously been given.[7] Since relatively strong β^+ branches are present in the decay, only the strongest conversion-electron lines could be observed.

The relative intensities for γ rays and conversion electrons are summarized in Tables I and II. Conversion coefficients are calculated wherever possible and inferred multipolarities are listed.

To aid in the construction of a decay scheme, the 40-cm^3 and 65-cm^3 Ge(Li) detectors were employed in an event-by-event γ-γ-t coincidence experiment. The detectors, placed 180° apart, were used in conjunction with standard electronics and yielded a total experimental resolving time of 12 nsec. A total of 15×10^6 events was obtained. Gates were subsequently set on most of the transitions assigned to the decay and corrected for random events and for the contribution from the Compton background beneath the gated γ ray. The proposed decay scheme consistent with the coincidence results is given in Table III.

Logft values (Table III) have been calculated for each of the proposed levels from the intensity imbalance for that level. The total disintegration energy was taken as $Q_{EC} = 6.7$ MeV, an average of the values given by the Wapstra (6.80 MeV) and the Garvey-Kelson (6.59 MeV) mass tables.[8] The γ-β^+ coincidence results of Li *et al.*[4] report the same observed β^+ end point (3.2 ± 0.4 MeV) for positrons

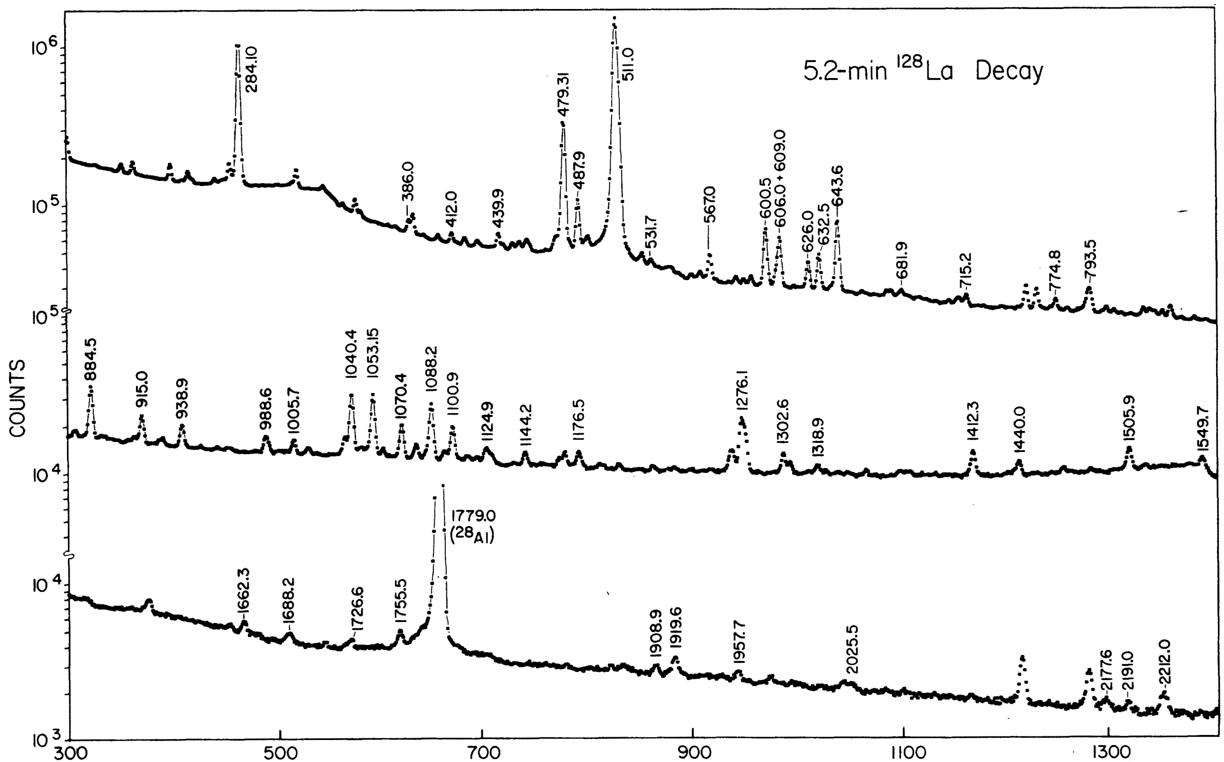

FIG. 1. γ-ray spectrum from 5.2-min ^{128}La obtained using the He-jet technique. Approximately 600 separate sources were counted.

TABLE I. Transition data for the decay of ^{128}La (5.2 min).

E_γ (keV)	I_γ	Placement	E_γ (keV)	I_γ	Placement
284.10(8)	1000	284.1 → 0	1036.3(3)	23.5(20)	1799.7 → 763.4
315.8(6)	6.3(12)	2246.7 → 1931.4	1040.4(2)	114(7)	1324.5 → 284.1
386.0(3)	18.9(15)	2425.5 → 2039.6	1045.7(5)	10.7(14)	
412.0(5) [a]	6.3(32)	2451.4 → 2039.5	1049.1(7) [b]	8.3(16)	2848.5 → 1799.7
427.4(3)	9.0(15)	1799.7 → 1372.4	1053.15(20)	117(7)	2425.5 → 1372.4
439.9(3)	23.9(20)	1324.5 → 884.5	1070.4(2)	51.6(30)	1833.8 → 763.4
451.6(7)	6.3(14)	2627.2 → 2175.7	1079.0(3)	19.7(20)	2451.4 → 1372.4
475.4(5)	23.3(35)	1799.7 → 1324.5	1088.2(2)	102(7)	1372.4 → 284.1
479.31(10)	614(30)	763.4 → 284.1	1100.9(3)	53.0(35)	2425.5 → 1324.5
483.1(4)	10.2(15)	2878.3 → 2395.6	1124.9(5)	6.3(12)	2531.9 → 1407.0
487.9(2)	115(6)	1372.4 → 884.5	1144.2(4)	17.8(17)	1907.6 → 763.4
493.9(4) [a]	13.4(31)	2425.5 → 1931.4	1164.9(5)	10.2(10)	2571.6 → 1407.0
531.7(4)	10.2(10)	2571.6 → 2039.5	1168.0(3)	18.5(15)	1931.4 → 763.4
561.0(3)	12.4(10)	1324.5 → 763.4	1176.5(10)	13.7(35)	1939.4 → 763.4
567.0(2)	44.4(30)	1939.4 → 1372.4	1276.1(5)	55.5(60)	2039.5 → 763.4
570.6(6)	3.4(10)	2746.3 → 2175.7	1302.6(6)	14.9(20)	2627.2 → 1324.5
587.3(5)	7.6(20)	2627.2 → 2039.5	1318.9(6)	12.8(20)	2203.5 → 884.5
591.7(4)	11.5(15)	2425.5 → 1833.8	1348.4(6) [b]	6.8(21)	2721.0 → 1372.4
600.5(2)	120(7)	884.5 → 284.1	1412.3(3)	40.0(30)	2175.7 → 763.4
606.9(4)	22.4(20)	1931.4 → 1324.5	1440.0(5)	20.8(22)	2203.5 → 763.4
609.0(3)	93.8(60)	1372.4 → 763.4	1482.8(7)	4.2(12)	2246.7 → 763.4
626.0(2)	43.8(25)	2425.5 → 1799.7	1505.9(4)	40.9(32)	2878.3 → 1372.4
632.5(2)	63.6(36)	2039.5 → 1407.0	1515.3(7)	6.7(13)	1799.7 → 284.1
643.6(2)	169(10)	1407.0 → 763.4	1549.7(4)	15.8(30)	1833.8 → 284.1
658.0(6) [b]	4.7(19)		1605.4(4)	17.0(20)	2978.1 → 1372.4
673.0(4) [b]	6.9(17)	2848.5 → 2175.7	1654.1(7) [b]	5.7(15)	2978.1 → 1324.5
675.7(4) [b]	6.9(14)		1662.3(5)	11.2(20)	2425.5 → 763.4
681.9(4) [b]	8.1(20)		1688.2(10) [b]	4.9(12)	2451.4 → 763.4
715.2(5)	6.9(12)	2039.6 → 1324.5	1710.7(10)	4.2(10)	2474.1 → 763.4
774.8(4)	15.7(20)	2978.1 → 2203.5	1722.8(9) [b]	3.5(13)	
781.8(5) [b]	3.9(12)	2721.0 → 1939.4	1726.6(7)	7.1(20)	
793.5(7)	12.3(32)	2627.2 → 1833.8	1755.5(4)	14.1(16)	2039.6 → 284.1
827.9(4) [b]	10.2(11)	2627.2 → 1799.7	1908.5(6)	6.5(12)	2192.6 → 284.1
838.9(4)	9.5(10)	2878.3 → 2039.5	1919.6(4)	14.1(15)	2203.5 → 284.1
884.5(2)	92.7(60)	884.5 → 0	1957.7(8)	6.0(10)	2721.0 → 763.4
915.0(3)	40.0(30)	1799.7 → 884.5	2025.5(8) [b]	3.9(12)	
938.9(3)	29.7(27)	2878.3 → 1939.4	2177.6(7) [b]	5.0(10)	
988.6(4)	13.0(13)	2395.6 → 1407.0	2191.0(8) [b]	3.7(14)	
1005.7(3)	16.6(15)	2412.7 → 1407.0	2212.0(6)	9.7(14)	2975.4 → 763.4

[a] Intensity determined from coincidence experiment.

[b] Tentatively assigned to ^{128}La decay.

coincident with the 284 and 479 keV gates as well as for a gate set on all transitions above 511 keV. This measured end point undoubtedly corresponds to the dominant (EC + β^+) branch to the 2425.5-keV level proposed in the present work. This assumption leads to $Q_{EC} = 6.65$ MeV, a result consistent with the value adopted.

Since no EC + β^+ feeding is observed to 2^+ states and since states with spins and parities ranging from 3^+ to 6^+ are apparently fed directly in the ^{128}La decay, a 5^- assignment seems most likely for the parent ground state.

The multispectral-scaling technique was used to monitor the decay of the 284-keV transition, from which the ^{128}La half-life was measured to be 5.2 ± 0.4 min.

III. DISCUSSION

A. Level structure

The quasiground-state band in ^{128}Ba is known from an in-beam study[5] up to the 12^+ level but is observed in the ^{128}La decay only up to the 1407-keV (6^+) state. Some population of the 8^+ state is possible, however, since the weak 781.8-keV γ ray, which has tentatively been placed between the 2721.0-keV and 1939.4-keV levels, could depopulate the known 2188-keV (8^+) state.

The present work supports the existence of a low-lying quasi-γ band in ^{128}Ba consisting of the 884.5-keV (2^+), 1324.5-keV (3^+), 1372.4-keV (4^+), and 1931.4-keV (5^+) states. The conversion coefficient data are consistent with these assignments.

TABLE II. Conversion coefficient data for the decay of ^{128}La (5.2 min).

E_γ (keV)	I_K	α_K (units 10^{-2}) Exp.	Theo.	Mult.
284.10(8)	43.7	≡43.7	$E2$: 4.37	$E2$
479.31(10)	5.42(30)	0.88(7)	$E2$: 0.93	$E2$
487.9(2)	1.17(27)	1.02(25)	$E2$: 0.91	$E2$
600.5(2)	0.69(25)	0.58(23)	$E2$: 0.51	$E2$, ($M1$)
609.0(3)	0.35(22)	0.37(24)	$E2$: 0.49	$E2$
632.5(2)	0.50(20)	0.79(32)	$M1$: 0.65	$M1$, ($E2$)
643.6(2)	0.91(30)	0.54(17)	$E2$: 0.43	$E2$

The location of members of the quasi-γ band in other Ba isotopes is shown in Fig. 2. An interesting feature with decreasing neutron number is the close bunching of the 3^+ and 4^+ states. This can be attributed to γ instability, a feature discussed in more detail elsewhere in this paper.

Since the ^{128}La spin is probably 5, it is likely that the 6^+ member of the quasi-γ band should also be populated. This state would decay strongly to the 4_γ^+ level. The level at 1939.4 keV not only meets this requirement but its close proximity to the 5_γ^+ state is consistent with the observed bunch-

TABLE III. Decay scheme for 5.2-min ^{128}La (5^-).

Level (keV)	I^π	I (EC+β^+) (%)	logft[a]	Depopulating transitions (level fed)[b] (keV)
284.10	2^+			284.1(g.s.)
763.41	4^+	5.0	7.0	479.31(284.1)
884.5	2^+			600.5(284.1), 884.5(g.s.)
1324.5	3^+	2.2	7.1	439.9(884.5), 561.0(763.4), 1040.4(284.1)
1372.4	4^+	5.0	6.7	487.9(884.5), 609.0(763.4), 1088.2(284.1)
1407.0	6^+	7.0	6.6	643.6(763.4)
1799.7	$3^\pm, 4^+$	3.7	6.6	427.4(1372.4), 475.4(1324.5), 915.0(884.5), 1036.3(763.4), 1515.3(284.1)
1833.8	$3^\pm, 4^+$	4.0	6.6	1070.4(763.4), 1549.7(284.1)
1907.6		1.6	7.0	1144.2(763.4)
1931.4	5^+	2.0	7.2	606.8(1324.5), 1168.0(763.4)
1939.4	(6^+)	2.3	6.8	567.0(1372.4), 1176.5(763.4)
2039.5	(5^+)	7.8	6.3	632.5(1407.0), 1276.1(763.4)
2039.6	(2^-)			715.2(1324.5), 1755.5(284.1)
2175.7	(4^-)	2.2	6.7	1412.3(763.4)
2192.6		0.6	7.3	1908.5(284.1)
2203.5	$3^\pm, 4^+$	2.9	6.6	1318.9(884.5), 1440.0(763.4), 1919.6(284.1)
2246.7	$4^-, 5^\pm, 6^+$	1.0	7.0	315.8(1931.4), 1482.8(763.4)
2395.6				988.6(1407.0)
2412.7	(7^-)	1.5	6.7	1005.7(1407.0)
2425.5	(4^-)	24.7	5.5	386.0(2039.6), 493.9(1931.4), 591.7(1833.8), 626.0(1799.7), 1053.15(1372.4), 1100.9(1324.5), 1662.3(763.4)
2451.4	$4^-, 5^\pm, 6^+$	2.8	6.5	412.0(2039.5), 1079.0(1372.4), $\underline{1688.2}$(763.4)
2474.1		0.4	7.3	1710.7(763.4)
2531.9		0.6	7.1	1124.9(1407.0)
2571.6	$5^-, 6^\pm$	1.9	6.6	531.7(2039.5), 1164.9(1407.0)
2627.2	$4^-, 5^+$	4.7	6.2	451.6(2175.7), $\underline{587.3}$ (2039.5), 793.5(1833.8), $\underline{827.9}$(1799.7), 1302.6(1324.5)
2721.0		1.5	6.6	$\underline{781.8}$(1939.4), $\underline{1348.4}$(1372.4), $\underline{1957.7}$(763.4)
2746.3		0.3	7.3	$\underline{570.6}$(2175.7)
2848.5		1.4	6.5	$\underline{673.0}$(2175.7), $\underline{1049.1}$(1799.7)
2878.3	(5^-)	8.3	5.8	483.1(2395.6), 838.9(2039.5), 938.9(1939.4), 1505.9(1372.4)
2975.4		0.9	6.7	2212.0(763.4)
2978.1	$4^-, 5^+$	3.5	6.1	774.8(2203.4), 1605.4(1372.4), $\underline{1654.1}$(1324.5)

[a] Reference 23. Q_{EC} is taken as 6.7 MeV.

[b] Transitions underlined are placed on the basis of energy sums and differences. All other placements are based on coincidence experiment results.

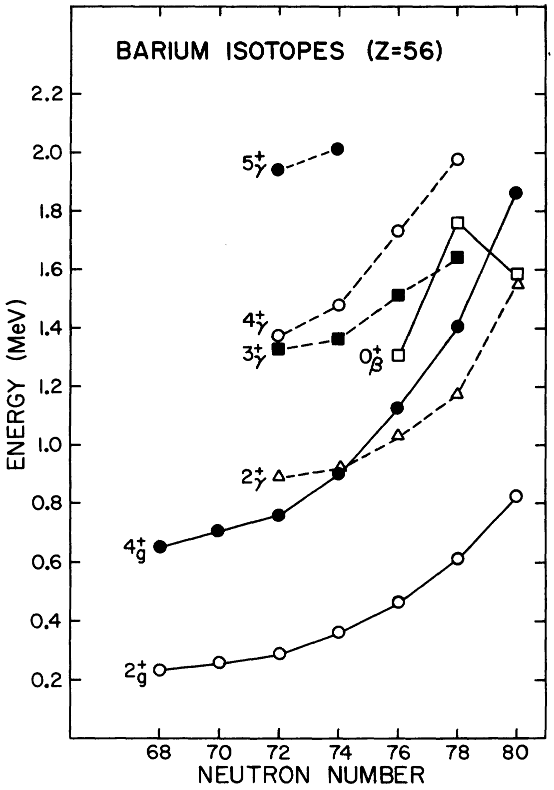

FIG. 2. The systematic behavior of quasiband members in Ba nuclei.

ing of the 3^+ and 4^+ states. However, the nonobservation of the decay of this state to the 6^+ member of the ground band is not consistent with the systematic trends for other 6^+ quasi-γ states. Nevertheless, since the branching to the 4^+_γ and 4^+_g is similar to that observed for the 6^+ state in ^{126}Xe,[9] the 1939.4-keV state is tentatively assigned to the quasi-γ band.

The ratios of reduced transition probabilities for the decay of the members of the quasi-γ band are given in Table IV where they are compared to those of neighboring nuclei and to the $N=88$ nuclei ^{152}Gd and ^{154}Dy. The similarity of these bands is apparent and supports the band assignments in ^{128}Ba.

2039 keV levels. The results of γ-γ coincidence experiments support the existence of at least two levels at approximately 2039 keV. This, for example, is apparent from the observation that the 386.0-keV γ ray is coincident with the 1755.5-keV transition but not with the 632.5-keV transition. The relevant coincidence data are given in Table V.

One level, assigned the energy 2039.6 keV, appears not to be fed directly in the EC + β^+ decay and depopulates to 2^+ and 3^+ states. A 2^- assignment

TABLE IV. $B(E2)$ ratios for quasi γ bands in transitional nuclei.

I_i	$I_f/I_{f'}$	^{126}Xe [a]	^{124}Xe [a]	^{130}Ba [b]	^{128}Ba	^{152}Gd [c,d]	^{154}Dy [d]	Theory (^{128}Ba) Symmetric rotor	Asymmetric rotor	Boson expansion [e]
2_γ	$0_g/2_g$	0.0148(7)	0.039(10)	0.052(1)	0.11(1)	0.142(14)	0.155(16)	0.70	0.13	0.048
3_γ	$2_g/4_g$	0.043(5)	0.19(5)	0.186(14)	0.42(4)	0.45(5)	0.27(3)	2.50	0.21	0.22
	$2_\gamma/4_g$	2.17(22)	6.4(16)	4.52	6.5(8)	<13		2.50	3.01	4.89
4_γ	$2_g/4_g$	0.011(2)		>0.028	0.060(6)	0.071(15)	0.036(10)	0.34		0.0027
	$2_\gamma/4_g$	1.05(3)	1.11(11)	>1.36	3.7(3)	3.4(14)	4.8(7)	0.34	1.35	2.00
5_γ	$3_\gamma/4_g$	20.1(15)	25.6(46)	40(6)	32(4)	39(3)	51(10)	0.60		41.8
	$6_g/4_g$			155(52)		5.4(5)	10(2)	0.57		10.7
	$3_\gamma/4_\gamma$	0.079(10)	1.02(28)			2.5(1)		1.00		1.87
6_γ	$6_g/4_g$	109(43)				17(4)	29(10)	3.71		15090
	$4_\gamma/6_g$	0.97(12)				9.3(27)		0.65		3.97
	$4_\gamma/5_\gamma$	0.082(18)						1.67		4.37
	$4_\gamma/4_g$	106(40)			124(33)			2.41		59850

[a] Reference 9.

[b] Reference 21 and R. A. Meyer (private communication).

[c] Reference 24.

[d] Reference 25.

[e] Calculated with $f=0.800$ and $g=0.703$.

TABLE V. Coincidence data supporting the existence of 2039.5-keV and 2039.6-keV levels.

Gated transition (keV)	Coincident transition[a] (keV)
386	284, 479, (715), (1276), 1756
412	284, 479, 633, 644, 1276
532	284, 632, 1276
633	284, 479, 644, 840
840	284, 479, 632, 644
1276	284, 479, (532)
1756	284, 386

[a] Parentheses indicate possible coincidences.

is consistent with these observations.

In an in-beam investigation of ^{128}Ba (Ref. 5), a level at 2039.2 keV has been proposed with a possible spin of 5. A similar state observed in ^{126}Ba is assigned as 5^+ by the same authors. The second state which we propose at 2039.5 keV appears to be this state. It is not clear, however, why the 632-keV transition was not reported in the in-beam study.

Two-quasiparticle states. A recent study of the level systematics of odd-mass La isotopes[10] suggests a $\frac{11}{2}^-$ assignment for the ground state of ^{125}La and possibly ^{127}La, and a $\frac{3}{2}^+$ ground state for ^{129}La (but with a low-lying $\frac{11}{2}^-$ isomer). The $\frac{11}{2}^-$ state is interpreted as the base state of a "decoupled band" which can occur for moderate deformations when the Coriolis interaction decouples the $h_{11/2}$ proton from the symmetry axis of the nucleus. The ground states of the odd-neutron nuclei ^{125}Xe, ^{127}Ba, and ^{129}Ba are probably $\frac{1}{2}^+$.[11,12] Consequently, the coupling $\pi_{11/2^-} \otimes \nu_{1/2^+}$ could account for the proposed 5^- assignment for ^{128}La. With this interpretation, however, it is difficult to account for the allowed β decays observed to the 2425.5-keV and 2878.3-keV levels.

We prefer an alternate interpretation. A Nilsson diagram for neutrons for $A \sim 140$ according to Ragnarsson, taken from Ref. 12, is given in Fig. 3. For moderate deformations the 71st neutron should be in the $\frac{7}{2}^+[404]$, $\frac{7}{2}^-[523]$, $\frac{5}{2}^+[402]$, or possibly the $\frac{1}{2}^+[411]$ orbital. Available proton states are $\frac{1}{2}^-[550]$, $\frac{3}{2}^+[411]$, $\frac{3}{2}^+[422]$, and $\frac{9}{2}^+[404]$. Thus, the ^{128}La ground state can be interpreted as the $(\nu\frac{7}{2}^-[523] + \pi\frac{3}{2}^+[411])_{5^-}$ configuration. If the 2425.5-keV state is designated as $(\nu\frac{7}{2}^-[523] + \nu\frac{1}{2}[411])_{4^-}$, the low log*ft* value of 5.5 is explained, since only a spin-flip is involved. The log*ft* value associated with the 2878.3-keV state is 5.8. This state might be interpreted as the $(\nu\frac{7}{2}^-[523] + \nu\frac{3}{2}^+[402])_{5^-}$ configuration. According to the original Alaga rules,[13] the β decay to this state is forbidden. However, as pointed out by Fujita, Emery, and Futami,[14] these rules must be modified to permit transitions for which $\Delta N = 0$ and $|\Delta n_z| = \Delta\Omega = \pm 1$. Transitions of this type, previously classed as allowed hindered, can be expected to have log*ft* values in the allowed-unhindered range.

A state at 2412.7 keV is observed in the ^{128}La decay which has been reported in a (HI, *xn*) reaction study.[5] The latter investigation proposes a spin of 7 for this state and notes that two-quasiparticle-plus-rotor calculations support a two-quasiproton configuration with negative parity. Such a configuration would not be expected to be fed directly in the ^{128}La decay. However, since this state is not strongly populated, it is possible it is fed by several weak and unobserved transitions from higher-lying states.

B. Theoretical considerations

A model for a γ-unstable nucleus was first proposed by Wilets and Jean and subsequently discussed by others.[3] Rohozinski, Srebrny and Horbaczewska[3] recently investigated a model which adds a γ-dependent term to the Wilets-Jean Hamiltonian and, using the perturbation method, applied

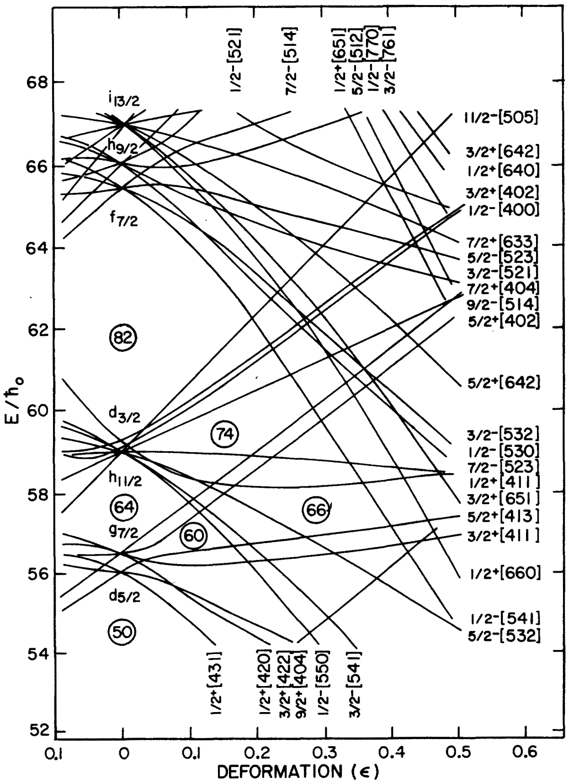

FIG. 3. Nilsson diagram for neutrons ($A \approx 140$) according to Ragnarsson (taken from Ref. 12).

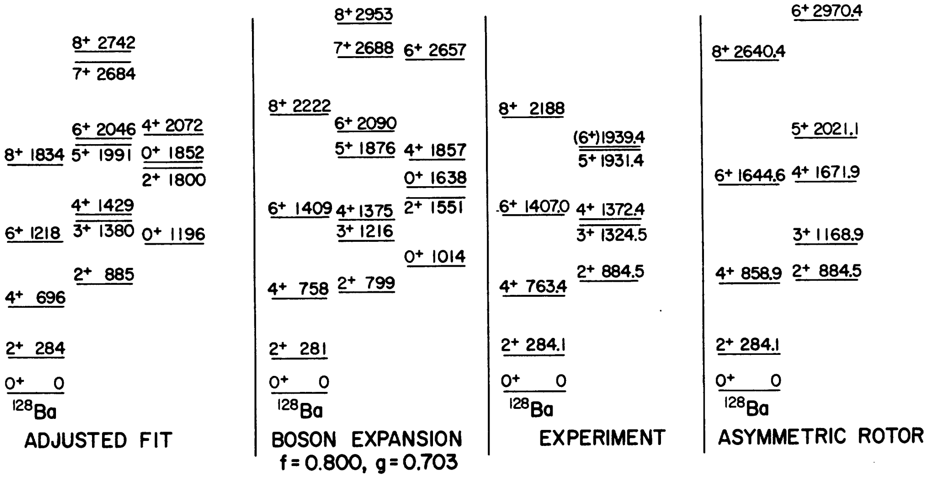

FIG. 4. Comparison of calculated and experimental energy levels for ^{128}Ba. The "adjusted fit" is a variation of the boson expansion and is discussed in the text. For the asymmetric rotor calculation $\gamma = 21.83°$.

this model to several Xe, Ba, Ce, and Nd nuclei. Such a treatment is not applicable to ^{128}Ba, however, since for a nucleus to be truly γ unstable, it is required that $E_2/E_1 \leq 2.5$. This ratio in ^{128}Ba is 2.69.

Gneuss, Mosel, and Greiner[15] have studied a series of deformed but γ-independent potentials and the effects of subsequent inclusion of γ-dependent terms. They note that for a γ-soft nucleus the 0^+ quasi-β bandhead should arise from the third phonon and not the second and that this state should lie in energy above the quasi-γ 2^+ bandhead. They also point out (as do Kishimoto and Turner[3]) that the quasi-γ band shows degeneracies of pairs of states (3^+ and 4^+, 5^+ and 6^+, etc.), with such degeneracy removed only with inclusion of a γ-dependent term in the potential. The splitting of the pairs of γ-band states is therefore a very sensitive indicator of the degree of γ instability in a nucleus. Since in ^{128}Ba the 3^+ and 4^+ states are split by only 48 keV, a very small prolate-oblate difference is possible.

We have applied the asymmetric-rotor model[16] to ^{128}Ba. The results are given in Fig. 4 and Table IV. In spite of the fact that numerous calculations of potential-energy surfaces provide little support for rigid triaxial shapes, this macroscopic model has been reasonably successful in describing the properties of many even-A nuclei (as has the particle-plus-rigid-triaxial-rotor model for odd-A nuclei[17]). Yamazaki, however, has provided an explanation, by noting that the rigid-asymmetric-rotor models do not necessarily indicate physical triaxial shape since they can include the case of a γ vibration about a symmetric rotor.[18] In general, the agreement for ^{128}Ba is only fair.

The microscopic code of Kishimoto and Tamura,[19] which describes nuclear collective motions in terms of the boson-expansion technique, was also used to calculate the level structure and electromagnetic properties of ^{128}Ba. In the theory, the microscopic Hamiltonian is written in terms of fermion creation and annihilation operators and the two basic bilinear products of the operators are expanded in powers of boson creation and annihilation operators. Although the expansion is only carried out to fourth order, the code represents an improvement of a previous version[20] in that the contributions of the quadrupole pairing

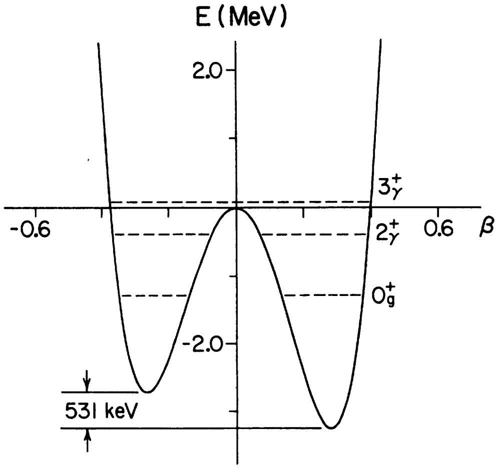

FIG. 5. The potential well obtained for ^{128}Ba from an adjusted fit. To ensure correspondence between the potential well and the observed energy spectrum, third- and fourth-order kinetic energy terms in the Hamiltonian have been eliminated using a canonical transformation.

TABLE VI. Comparison of present estimate of prolate-oblate difference in MeV for ^{128}Ba with theoretical calculations for $N=72$ nuclei.

	^{128}Ba				^{130}Ce	
	Present estimate	Ragnarsson *et al.*[a]	Pomorska *et al.*[a]	Arseniev *et al.*[a]	Götz *et al.*[a]	Pomorska *et al.*[a]
$\lvert V_{pr}\rvert - \lvert V_{ob}\rvert$	0.5	1.65	0.0	−0.4	0.5	0.2

[a] Reference 2.

interaction and the interaction of collective and noncollective bosons have also been included. This model contains only two parameters, f and g, the strengths of the quadrupole particle-hole and quadrupole pairing interactions, respectively. The results of this calculation are included in Fig. 4 and Table IV, where they are compared with experiment. The agreement is excellent for a microscopic approach. An interesting point is that the calculation also predicts a low-lying 0^+ state. No clear-cut candidates for members of a quasi-β band are observed in the decay of ^{128}La. However, as can be seen from Fig. 2, a low-lying 0^+ state is possible on the basis of systematic trends. This is further supported by the observation of a possible 2^+ quasi-β state in ^{130}Ba at 1557 keV (Ref. 21), suggesting a low-lying 0^+ state in that nucleus.

Needed are ^{130}Ba(p,t) and ^{130}Ba(d,d') reaction studies to locate the low-lying 0^+ states in ^{128}Ba and ^{130}Ba. Additional members of both the quasi-β and quasi-γ bands in ^{128}Ba might possibly be observed in in-beam investigations using the ^{133}Cs$(p,6n\gamma)$ or ^{127}I$(^7$Li$,6n\gamma)$ reactions.

The microscopic boson-expansion calculation bunches the 3^+ and 4^+ quasi-γ states but does not reproduce the very close spacing (48 keV) observed experimentally. Since this splitting is sensitive to the degree of γ instability and since an estimate of the prolate-oblate difference has theoretical significance, an attempt was made to slightly vary the microscopically obtained coefficients of the Hamiltonian to obtain a better fit. An estimate of the prolate-oblate difference requires a proper characterization of the lower part of the potential surface. The important features to be reproduced, therefore, are the 2_g^+ and 2_γ^+ energies and, of course, the 3_γ^+ and 4_γ^+ splitting. Using these guidelines, an adjusted fit was obtained and is given in Fig. 4.

Since the Hamiltonian contains anharmonic kinetic energy terms, it is possible that the potential surface does not correspond exactly to the observed energy spectrum. Consequently, the prolate-oblate difference may be inaccurate. To remedy this, a canonical transformation of the Hamiltonian[19] was performed to eliminate third and fourth order kinetic energy terms. The resulting potential surface is more "realistic," that is, the energy spectrum can be deduced from the shape of the potential energy surface.

The prolate-oblate difference finally obtained, consistent with the experimental energy spectrum, is approximately 0.5 MeV as shown in Fig. 5. This value is compared with the predictions of several potential-energy surface calculations in Table VI and is found to be consistent with their indication that ^{128}Ba is nearly γ unstable.

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