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Levels in ^{148}Ce from the decay of mass separated ^{148}La

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The level scheme of ^{148}Ce populated by β decay of ^{148}La, produced in thermal neutron fission of ^{235}U, has been studied. Ion beams of mass 148 were separated by an on-line isotope separator and deposited on a movable tape. Gamma-ray singles, γ-γ time, γ-γ angular correlations, and time sequenced γ and β spectra were collected. The half-life for ^{148}La was measured to be 1.05 ± 0.01 s. A level scheme for ^{148}Ce is presented including several members of the ground, β, γ, and octupole bands. The resulting level scheme has been compared with other $N=90$ nuclides and with interacting-boson-approximation-2 calculations.

[RADIOACTIVITY ^{148}La [from ^{235}U($n_{\rm th}$,f)] measured $t_{1/2}$, E_γ, I_γ, $\gamma\gamma t$ coincidence, $\gamma\gamma(\theta)$ angular correlation; HPGe and Ge(Li) detectors; ^{148}Ce deduced levels, J^π and I_β. Mass-separated ^{148}Ba activity. IBA-2 calculations: $E_{\rm level}$ and $B(E2)$.]

I. INTRODUCTION

The rare earth region of deformed nuclei has been studied very extensively in the past three decades. The investigations provided detailed knowledge for many of these nuclides and revealed impressive examples of smooth systematic behavior of nuclear properties over a wide range of masses. Yet, there are parts of this region near shell closures where information remains incomplete. Nuclides just above the $Z=50$ closed shell with $N>82$ have not been well characterized because these isotopes are not easy to observe experimentally. They are neutron rich, often with very short half-lives, and at present can only be produced by nuclear fission or spallation reactions and then only with small cross sections. Efficient, rapid separation techniques are needed for these investigations. Recently the level schemes of neutron-rich even Ba isotopes ($Z=56$) were studied.[1] Evidence was found to suggest that the onset of deformation as signaled by the minimization of 0_2^+ level systematics occurs at lower neutron numbers in Ba than for isotopes with higher Z (Nd, Sm), where it is known to be situated at $N=90$. The mass separator TRISTAN (Refs. 2–4) at the High Flux Beam Reactor (HFBR) of the Brookhaven National Laboratory offers the capability to study the neutron-rich Ce isotopes through the β decay of their La parents. This investigation of ^{148}Ce was undertaken in order to find and characterize the low-lying levels of this isotope and thus extend the systematics of the $N=90$ isotones. In particular, it is of interest to investigate and compare the level systematic behavior of Ce with that of Ba and Nd.

Prior to the present investigation, information had been published on the half-life of ^{148}La and on a few γ transitions in ^{148}Ce. For the half-life of the β decay of ^{148}La values of $t_{1/2}=1.29\pm0.08$ s,[5] $t_{1/2}=1.7\pm0.5$ s,[6] and $t_{1/2}=2.61\pm0.61$ s (Ref. 7) have been reported. Gamma transitions of 386, 295, and 159 keV have been attributed to ^{148}Ce as the $6^+\to4^+\to2^+\to0^+$ cascade of the ground state band.[8] Several of these transitions were also observed in other studies.[5,9–16] The results of conversion electron spectroscopy[9,13] and of angular correlation measurements[15] support the spin assignments.

The lifetime of the 2_1^+ level at 159 keV was measured as 1.06 ± 0.08 ns (Refs. 5 and 17), from which a value of the deformation parameter $\beta_2=0.25$ ±0.02 was deduced. Evidence for two additional γ transitions of 379 and 538 keV (Ref. 16) was proposed as depopulating a level at 538 keV.

II. EXPERIMENTAL TECHNIQUES

A. The mass separator TRISTAN

The TRISTAN mass separator facility[2,3,4,18] is installed at the exit port of a radial beam tube of the HFBR. For the studies of the La decays a surface ionization source[19] is used. About 5 g of 93% enriched ^{235}U impregnated into a graphite cloth cylinder is used as the fissioning target. The cylinder (3 cm length $\times 2$ cm diameter) located inside the ion source is exposed to a flux of about 1.5×10^{10} neutrons per cm^2 per second and is heated by electron bombardment to approximately 2200 °C. Fission products diffuse through the graphite matrix, evaporate, and are ionized on a hot Re surface. Separation according to mass is achieved using a 90° magnet and the resultant ion beam is focused onto a movable tape which may be stepped in a repetitive sequence in front of detectors.[20]

The isobars ^{148}Cs, ^{148}Ba, and ^{148}Pr were present in the separated ion beam of ≈ 200 atoms/s. The Ba isotope accounted for 50% of the total beam. A 20% Ge(Li) detector and a thin-window, 16%-HPGe detector were used to record γ spectra of the ^{148}La activity.

B. Gamma-ray singles measurements

Data were recorded using a custom-designed multitask PDP 11/20 at the HFBR.[2,18] Gamma-ray spectra were taken at the place where the ion beam of fission products (which forms a line of 1 mm width and 5 mm height) is deposited onto the tape (the parent port). The tape was moved at 4 s intervals in order to suppress the detection of radiations from long-lived $A=148$ isobars. These spectra were used to determine energies and relative intensities of γ rays.

In a separate experiment time-sequenced gamma-ray spectra were registered in the multiscaling mode using a Ge(Li) detector. The ion beam was deposited for 3 s, then deflected for 4 s, during which 32 spectra were recorded at time intervals of 0.125 s. The tape was then moved 15 cm to a shielded location and the cycle repeated. The multiscaling measurements were used to determine the half-life of ^{148}La and to help in the assignment of γ transitions to this decay.

C. Coincidence experiments

The detectors were positioned 180° apart at the parent port during the γ-γ coincidence measurements. They were both at a distance of 1 cm from the source. The tape was moved at intervals to enhance the ^{148}La decay. The addresses derived from the energy signals and the time relationship between responses from both detectors were encoded in event-by-event mode on magnetic tape. About 10^6 γ-γ-t events from the decay of ^{148}La were recorded.

D. Angular correlation measurements

A γ-γ angular correlation experiment was performed using a four detector system developed at TRISTAN and described by Wolf *et al.*[21] Briefly, the system uses four HPGe detectors positioned at intervals of 60°, 90°, and 75° in a coplanar geometry, allowing the simultaneous measurement of correlated data at six angles: 15°, 30°, 45°, 60°, 75°, and 90°. Data are collected and stored on magnetic tape in an event-by-event fashion which encodes the detector pair recording a coincident event along with the energy and timing information for the event. The event mode tapes are then scanned for the desired energy gates as well as for a selected angle (detector pair). Each spectrum is normalized for detector response using singles spectra from each detector accumulated simultaneously during the run. To remove any discriminator effects, the event trigger for the coincidence unit (the constant fraction discriminator output) is also used to gate the normalization spectra.

For the ^{148}La experiment, the detectors were placed at a position that was shielded from the point where the ion beam was deposited and as close to the source as possible. Two detectors were positioned 5 cm from the source, the third was at 4.8 cm, and the fourth was at 6.4 cm from the source. The ion beam was collected for 2 s, followed by a tape move (to the source position) and decay time of 1 s to allow the ^{148}Ba to decay, then data were accumulated during the next 2 s interval. The experiment ran continuously for 18 d, during which 2.4×10^6 events were collected.

III. RESULTS

A. Singles measurements

A portion of a singles γ-ray spectrum from the HPGe detector is shown in Fig. 1. The major γ transitions which are assigned to the β decay of ^{148}La are indicated. There are contributions from $A=148$ isobars, from the Ge(n,γ) reaction inside

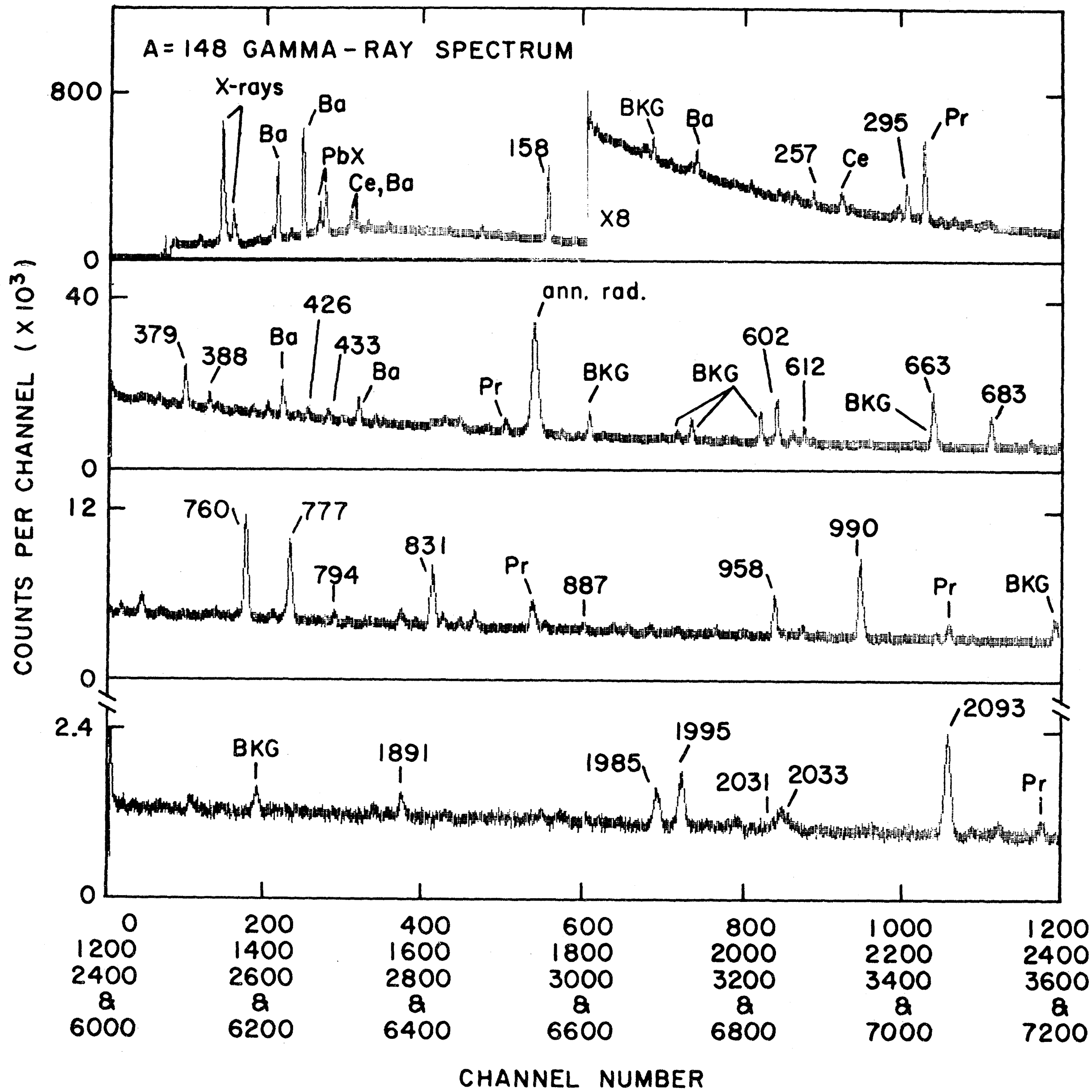

FIG. 1. A portion of a singles γ-ray spectrum measured with the HPGe detector during 72 h. The energy of the stronger γ rays from the decay of ^{148}La are identified along with major contaminant lines.

the detector, and from other typical reactor background sources (^{41}Ar, ^{60}Co, ^{137}Cs, and ^{40}K). Because of these contributions the assignment of the γ transitions to ^{148}La could not be deduced merely from the singles spectra but were also based on the results of the multiscaling measurements and on the coincidence data.

The information on the energies and relative intensities of the γ transitions (normalized to 1000 for the 158-keV transition) in ^{148}Ce is compiled in Table I. Gamma transitions with intensities as low as six relative units were observed in the present study. Figure 2 shows one of the results of the γ multiscaling measurements. The decay curve was obtained from the decay of the 158-keV γ ray. The half-life of ^{148}La was obtained by least squares analysis of these data, fitting the curve to a three-component exponential (^{148}Cs, ^{148}Ba, and ^{148}La) yielding a value of 1.05$\pm$0.01 s with the Cs and Ba half-lives fixed at 0.13 and 0.59 s, respectively.

TABLE I. Energies and intensities of the γ transitions in ^{148}Ce.

E_γ (keV)	I_γ[a]	E_γ (keV)	I_γ	E_γ (keV)	I_γ
54.24[b]					
158.47(7)	1000(20)[c]	760.30(6)	154(7)	1425.58(11)	16(1)
252.45(7)	30 (2)	770.53(10)	9(1)	1431.56(10)	24(1)
257.09(9)	6 (1)	777.16(6)	129(2)	1464.36(11)	16(1)
295.07(9)	120 (2)	794.44(11)	13(1)	1496.97(12)	11(1)
298.81(14)	13 (1)	819.28(8)	24(6)	1569.65(25)	7(2)
369.45(8)	12 (1)	831.33(6)	93(5)	1589.93(13)	15(1)
379.11(7)	71 (1)	887.12(12)	8(1)	1732.67(16)	12(1)
387.92(10)	25 (1)	921.31(13)	10(2)	1769.27(21)	16(2)
425.68(8)	18 (1)	958.23(6)	71(1)	1891.02(17)	22(1)
433.32(8)	20 (1)	967.40(40)	7(2)	1985.93(17)	44(1)
482.19(7)	17 (1)	989.85(6)	168(5)	1995.23(16)	59(2)
536.38(16)	9 (1)	1105.06(15)	6(1)	2031.17(20)	21(2)
601.88(6)	137 (2)	1130.95(10)	19(2)	2033.95(24)	12(2)
611.81(7)	52 (1)	1257.42(14)	11(1)	2093.66(21)	126(2)
654.53(11)	14 (4)	1298.46(25)	15(1)	2153.56(23)	13(2)
663.20(7)	27 (1)	1303.30(30)	2(2)	2219.89(25)	27(2)
682.97(6)	116 (9)	1316.69(18)	8(1)	2391.94(22)	70(5)
713.37(12)	9 (1)	1338.64(8)	32(2)	2549.80(60)	6(4)

[a]The intensities are normalized to $I_\gamma(158)\equiv 1000$ and are not corrected for internal conversion. The standard deviations are given in parentheses after the value expressed in terms of the last digit, for example: $158.47(7)\equiv 158.47\pm 0.07$.
[b]The 54 keV γ ray was not directly observed, but its existence and intensity could be deduced from the coincidence data.
[c]When internal conversion is included, $I(158)=1394$, based on $\alpha_{\text{tot}}=0.394$ for a pure $E2$ transition.

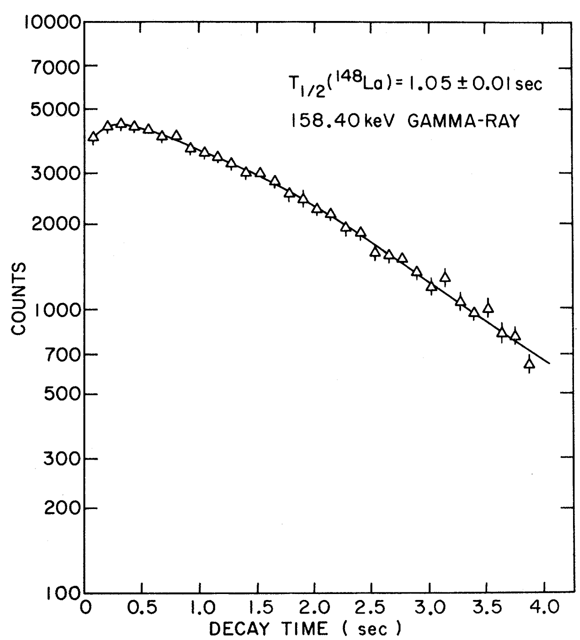

FIG. 2. Results of the multiscaling measurements for the 158.47-keV γ ray in ^{148}Ce.

B. Coincidence measurements

Two examples of γ-γ coincidence spectra are shown in Fig. 3. The total coincidence matrix is given in Table II along with the placement of each γ ray.

The level scheme of ^{148}Ce is shown in Fig. 4. It has not been constructed from coincidence information and the intensity of the 158-keV transition has not been corrected for internal conversion. Since most of the levels are depopulated through more than one γ transition, their energies are well established. Only three of the γ transitions listed in Table I were not incorporated into the scheme. Inspection of Table II shows that the 379- and 777-keV γ rays are in coincidence. This is possible only if there is a transition connecting the 990- and 936-keV levels, or if the 777-keV γ ray is given a double placement, feeding the 1369-keV level and depopulating the 936-keV level. The latter possibility can be ruled out since neither the 777- nor the 990-keV gate supports the double placement of the 777-keV γ ray. Therefore there must be an unobserved 54-keV transition connecting the 990- and 936-keV levels.

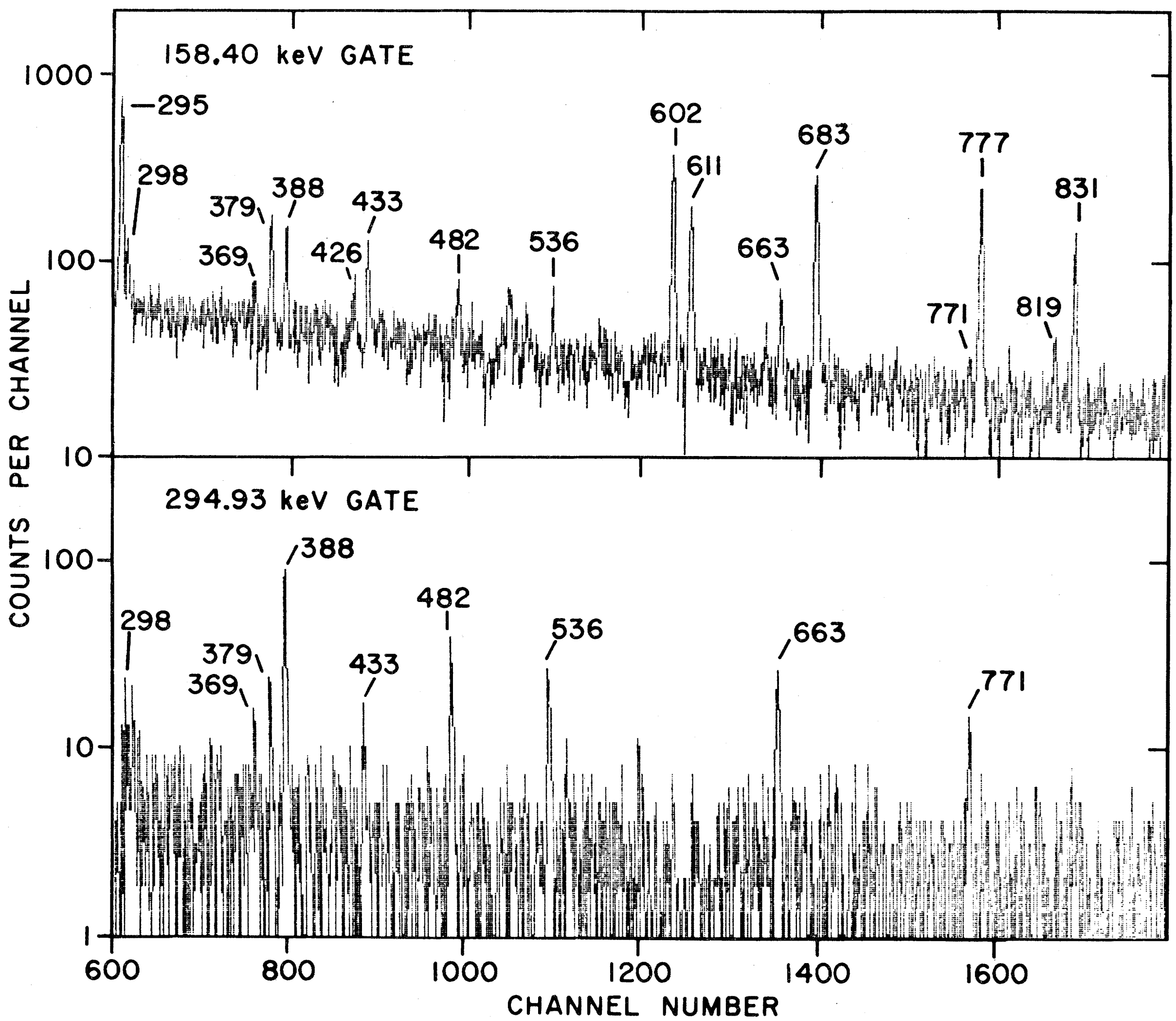

FIG. 3. Examples of coincidence spectra showing portions of two gates resulting from a 72 h experiment.

Quantitative analysis of the 379- and 777-keV gates gives an intensity of 9±3 [relative to $I(158)=1394$] to the 54-keV γ ray. If the transition is pure $E2$, then $\alpha_{\text{tot}}\approx 18$,[22] making the γ-*ray* intensity about 0.5. If the transition is pure $M1$, then $\alpha_{\text{tot}}\approx 7$,[22] making the γ-*ray* intensity about 1.3. Therefore, the γ-ray transition could not be observed in this experiment.

The β feedings have been calculated from intensity balances using relative γ-ray intensities corrected for internal conversion where possible. They do not take into consideration a possible β transition to the ground state of ^{148}Ce or unobserved γ population stemming from deexcitation of higher lying levels.[23] Since the mass 148 activity is low and the Q_β ($\geq 5862\pm 100$ keV) (Ref. 24) is rather high, the missing γ intensity is likely to be of significant magnitude. Therefore, the deduced β feedings should be interpreted as an upper limit. The fact that the 0_2^+ level (see Sec. IV) is only weakly fed in β decay suggests that the ground state feeding may not be strong. Significant β feeding occurs primarily to 2^+, 1^-, and 3^- levels; thus the most likely J^π for the ^{148}La ground state is 2^-. However, since missing γ intensity could substantially reduce some γ intensity balances, thereby altering the β-feeding pattern, ^{148}La ground state J^π values of 1^- and 3^- cannot be excluded. The intensity balance and β feeding deduced for each level (keeping the above assumptions and precautions in mind) are listed in Table III. Because significant missing γ intensity is expected, no arguments based on log*ft* values were used to assign J^π values for levels in ^{148}Ce.

The 2_1^+ and 4_1^+ levels, which were known earlier

TABLE II. Coincidence list and γ-ray assignments.

Gate	Gamma rays in coincidence (keV)						Assignment
158	252	295	299	369	379[a]	388	158→ 0
	426[a]	433	482	536	602	612	
	655	663	683	771	777	794[a]	
	819	831	887	921[b]	958	1105	
	1257	1298	1317	1339	1426	1432	
	1464	1733	1769	1986	1995	2031[b]	
	2034	2094	2392				
252	158	295[a]	958	663			1369→1117
257	158[a]	295[a]	379	831[a]	990[a]		1626→1369
295	158	252[a]	299[a]	369[a]	379[a]	388	453→ 158
	433[a]	482	536	663	771	1105	
299	158	295[a]	663	958			1416→1117
369	158	295[a]	958				1486→1117
379	158[a]	257	295[a]	536	777[a]	831	1369→ 990
	990						
388	158	295					841→ 453
426	158[a]	295[a]	831	990			1416→ 990
433	158	295[a]	482	777			1369→ 936
482	158	295	433				936→ 453
536	158	295	379				990→ 453
602	158	794					760→ 158
612	158	819					770→ 158
655	158	777					1590→ 936
663	158	252	295				1117→ 453
683	158						841→ 158
713	158	683					1555→ 841
760	794	967					760→ 0
770	158	295					1224→ 453
777	158	379[a]	433	655	1317		936→ 158
794	158[a]	602	760				1555→ 760
819	158	612					1590→ 770
831	158	379	426				990→ 158

(see Sec. I), are confirmed. No population of the 6^+ level has been observed in the present investigations. The level we observe at 841.35 keV is not the 6^+ level, the energy of which has been reported as 840.9 keV. The energy difference is outside the experimental uncertainties since the γ rays depopulating the 841.35- and 840.9-keV levels have clearly different energies: 387.92 (Table I) and 386.5 keV,[5] respectively. In any case, the observed γ deexcitation excludes spin 6 for the level at 841.35 keV. A level at 538 keV in ^{148}Ce (Ref. 16) could not be confirmed. The coincidence data require a different placement of the γ rays which were reported as deexciting this state (see Sec. I).

C. Angular correlation measurements

The primary intention of the angular correlation measurements was to confirm the suspected assignment of a level at 770 keV as an excited 0^+ state. Because of the low counting rate, about 100 counts per angle for a typical photopeak, the detectors were placed as close to the source as possible. The data were then corrected for the solid angle and detector response using the standard procedures described by Camp and Van Lehn.[27] The 612→158 keV cascade was found to have $A_2=0.22\pm0.09$ and $A_4=1.02\pm0.17$, identifying, unambiguously, the level at 770.27 keV as a 0^+ state. For a $0\rightarrow2\rightarrow0$ cascade the theoretical A_2 and A_4 values are 0.357 and 1.143, respectively. The results are shown in Fig. 5, where the solid line represents the curve obtained with the fitted A_2 and A_4 values. No other 0^+ states were identified. Spins of other states could not be determined from these data because the statistics were too poor and no correlations other than the very anisotropic $0\rightarrow2\rightarrow0$ could be measured with sufficient accuracy.

TABLE II. (Continued.)

Gate	Gamma rays in coincidence (keV)				Assignment
887	158	295[a]	388	683	1728→ 841
921[b]	158	602	760		not placed
958	158	252	299	369	1117→ 158
967	158[a]	602	760		1728→ 760
990	379	426			990→ 0
1105	158	295			1558→ 453
1131	158[a]	602	760		1891→ 760
1257	158				1416→ 158
1298	158				1457→ 158
1303	158	683			2144→ 841
1317	158	777			2252→ 936
1339	158				1497→ 158
1426	158				1584→ 158
1432	158				1590→ 158
1464	158				1623→ 158
1497	none				1497→ 0
1570	158				1728→ 158
1590	none				1590→ 0
1733	158				1891→ 158
1769	158				1928→ 158
1891	none				1891→ 0
1986	158				2144→ 158
1995	158				2154→ 158
2031[b]	158	602			not placed
2034	158				2192→ 158
2094	158				2252→ 158
2154	none				2154→ 0
2220[b]	none				not placed
2392	158				2550→ 158
2550	none				2550→ 0

[a]Observed in gated spectrum with lower intensity than expected for a direct cascade.
[b]Not placed in level scheme.

IV. DISCUSSION

A. Systematics

Although the 0_2^+ state is the only level which could be assigned an unambiguous spin and parity, it is instructive to examine possible assignments for other levels, using the deexcitation patterns of levels and the systematics of Ce isotopes (Fig. 6) and the $N=90$ isotones (Fig. 7) as a guide. The spin and parity assignments indicated outside the parentheses in Fig. 4 are the preferred assignments, while those inside the parentheses are other possibilities which cannot, rigorously, be excluded.

Both the systematics of the Ce isotopes and of the $N=90$ isotones suggest 1^- and 3^- levels with excitation energies between 500 and 1000 keV for ^{148}Ce. Furthermore, the separation of the 1^- and 3^- levels remains remarkably constant for the lighter $N=90$ isotones ranging from 78 keV for Sm to 82 keV for Ba. Good candidates for these states are levels at 760 and 841 keV, respectively. These assignments are supported by the deexcitation patterns and the separation energy of 81 keV.

Since the 0_2^+ state lies at 770 keV, it is possible that the level at 936 keV is the 2^+ member of the band built on the 0_2^+ state, commonly referred to as the β band. In the other $N=90$ isotones, the difference in energy between the 2_β^+ and 0_β^+ levels is approximately equal to the excitation energy of the 2_1^+ state. The deviation from this observation ranges from 3 to 45 keV. The 2_β^+ assignment to the 936-keV level would give a deviation of 8 keV from the 2_1^+ excitation energy. Furthermore, the fact that no transition from the 936-keV level to the ground state or the 0_β^+ state has been observed is in line with the

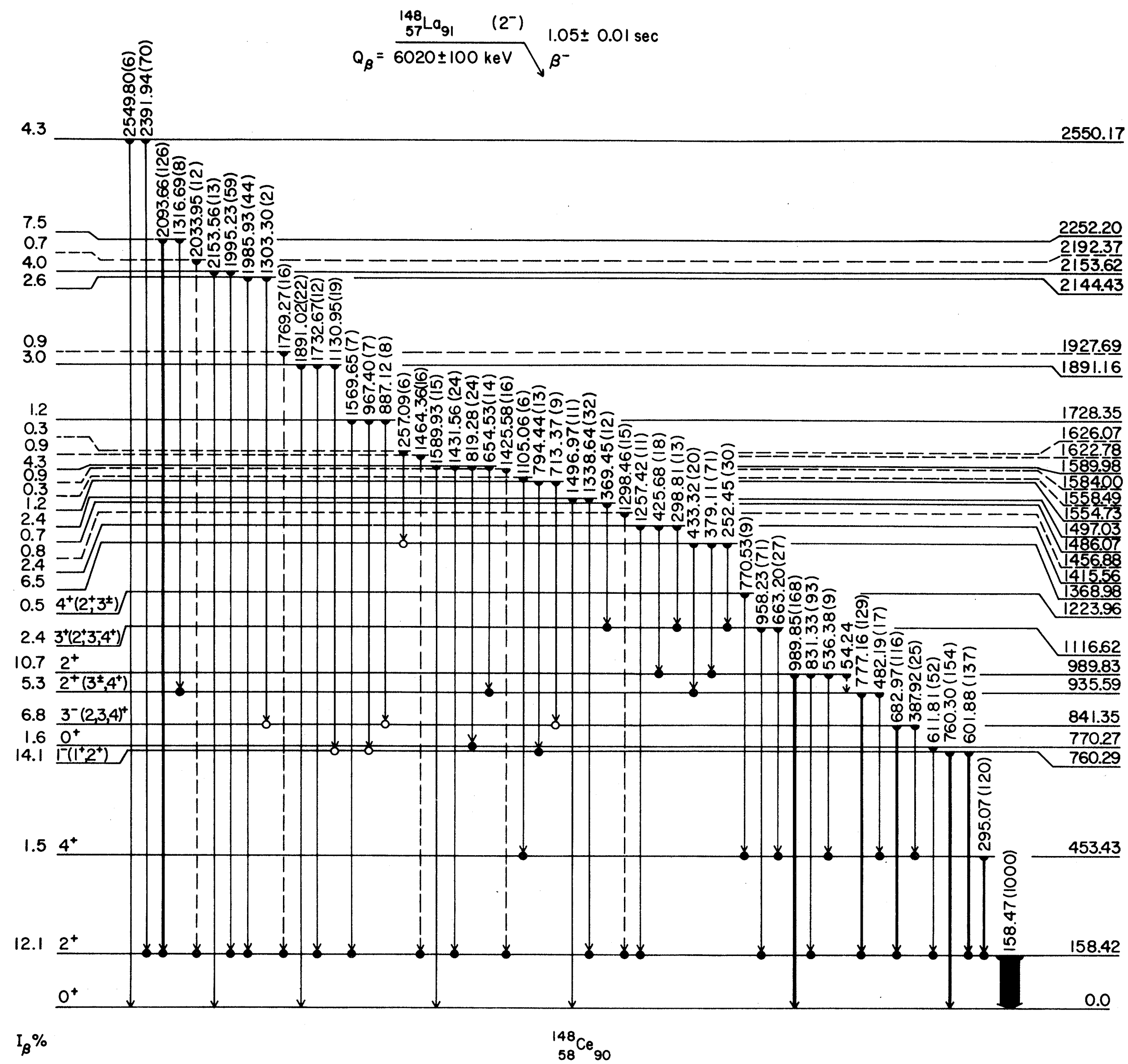

FIG. 4. The proposed level scheme of ^{148}Ce with the relative γ intensities given in parentheses adjacent to transition energies. The placement of all transitions is established through coincidence results. β-feeding percentages are shown to the left of the scheme. The preferred J^{π} assignments are indicated on the left end of the levels, with other values which cannot be rigorously excluded given in parentheses. See text for details.

generally weak $2_\beta^+ \rightarrow 0_1^+$ and $2_\beta^+ \rightarrow 0_\beta^+$ transitions in other $N=90$ isotones.

A candidate for the 4^+ member of the β band is proposed at 1224 keV. Assuming this assignment, the ratio $E(4_\beta^+/4_1^+)$ is 2.7, which compares favorably with the corresponding ratios of 2.5 to 2.7 for the heavier $N=90$ isotones. The deexcitation pattern is also consistent with those of the heavier isotones where the 4_β^+ state decays predominantly to the 4_1^+ state.

The level at 990 keV is possibly the 2^+ member of the γ band because it deexcites to the ground band 0_1^+, 2_1^+, and 4_1^+ states. The 3^+ member of this band might be the level at 1117 keV. The energy separation between 1117 and 990 keV is very similar to the energy difference $E(3_\gamma^+ - 2_\gamma^+)$ in ^{150}Nd, ^{152}Sm, and ^{154}Gd, 137, 148, and 135 keV, respectively. The 4_γ^+ state may be the level at 1369 keV, based on energy systematics for the $N=90$ isotones, but the deexcitation pattern is not very similar. In the heavier iso-

TABLE III. Energies, intensity balances, and β feedings for levels in ^{148}Ce.

Energy (keV)	Intensity balance	β feeding[a] (%)
0.0	−1783(22)	≡0.0
158.42(4)	216(24)	12.1(14)
453.43(6)	27(3)	1.51(17)
760.29(4)	252(8)	14.13(48)
770.27(7)	28(6)	1.57(34)
841.35(6)	122(9)	6.84(51)
935.59(5)	95(6)	5.33(34)
989.83(4)	190(8)	10.66(47)
1116.62(6)	43(3)	2.41(17)
1223.96(12)	9(1)	0.50(6)
1368.98(6)	115(3)	6.45(19)
1415.56(7)	42(2)	2.36(12)
1456.88(25)	15(1)	0.84(6)
1486.07(10)	12(1)	0.67(6)
1497.03(7)	43(2)	2.41(12)
1554.73(9)	22(1)	1.23(6)
1558.49(16)	6(1)	0.34(6)
1584.00(12)	16(1)	0.90(6)
1589.98(7)	77(7)	4.32(40)
1622.78(12)	16(1)	0.90(6)
1626.07(11)	6(1)	0.34(6)
1728.35(12)	22(3)	1.23(17)
1891.16(8)	53(2)	2.97(12)
1927.69(21)	16(2)	0.90(11)
2144.43(15)	46(2)	2.58(12)
2153.62(13)	72(3)	4.04(18)
2192.37(24)	12(2)	0.67(11)
2252.20(14)	134(2)	7.52(15)
2550.17(18)	76(6)	4.26(34)

[a] The β feedings were calculated assuming no ground state β feeding. The values in parentheses are the standard deviations derived from statistical considerations only and do not include estimates of contributions from unobserved γ rays.

tones, the 4_γ^+ decays predominantly to the 4_1^+ and 2_1^+ states. Another possibility for the 4_γ^+ state is the level at 1558 keV, which is observed to decay only to the 4_1^+ state and gives reasonable agreement with the energy systematics suggestions. However, it is not clear which of these levels, if indeed either, is the 4_γ^+ state.

Although these spin and parity assignments are by all means tentative, they form a best choice using the available data. Alternative band assignments lead to irregularities in the systematics while the proposed assignments yield very smooth systematics. This is especially true for the ground state, the β band, and the 1^- and 3^- levels.

It is of interest to inspect the ratios of $E_x/E_{2_1^+}$, where E_x is a nonground band state. These ratios

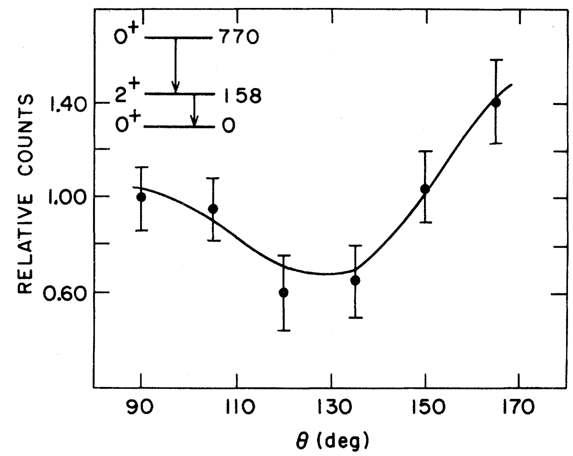

FIG. 5. The results of the angular correlation experiment, showing that the 770-keV level is a 0^+ state. For this cascade, $A_2=0.22\pm0.09$ and $A_4=1.02\pm0.17$.

give a good indication of the onset of deformation.[28] For convenience, $E(0_2^+/2_1^+)$ is plotted in Fig. 8 versus neutron number for Ba-Gd in the region relevant to this paper. For Nd, Sm, and Gd isotopes the ratio gradually increases with N to a value of about 3 in the vibrational area, drops slightly, and then rises sharply after $N=90$ to values above 10. The situation is different for Ba. Here the ratio rises continuously to $N=90$, which could indicate a more gradual change of nuclear shape. The investigations at TRISTAN show an intermediate situation

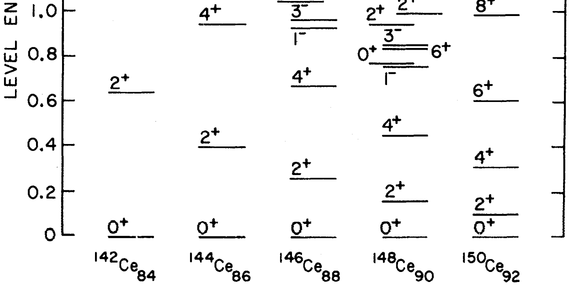

FIG. 6. Systematics of the even Ce isotopes. ^{142,144}Ce from Ref. 25, ^{146}Ce from Ref. 26, ^{148}Ce from the current work, and ^{150}Ce from Ref. 15.

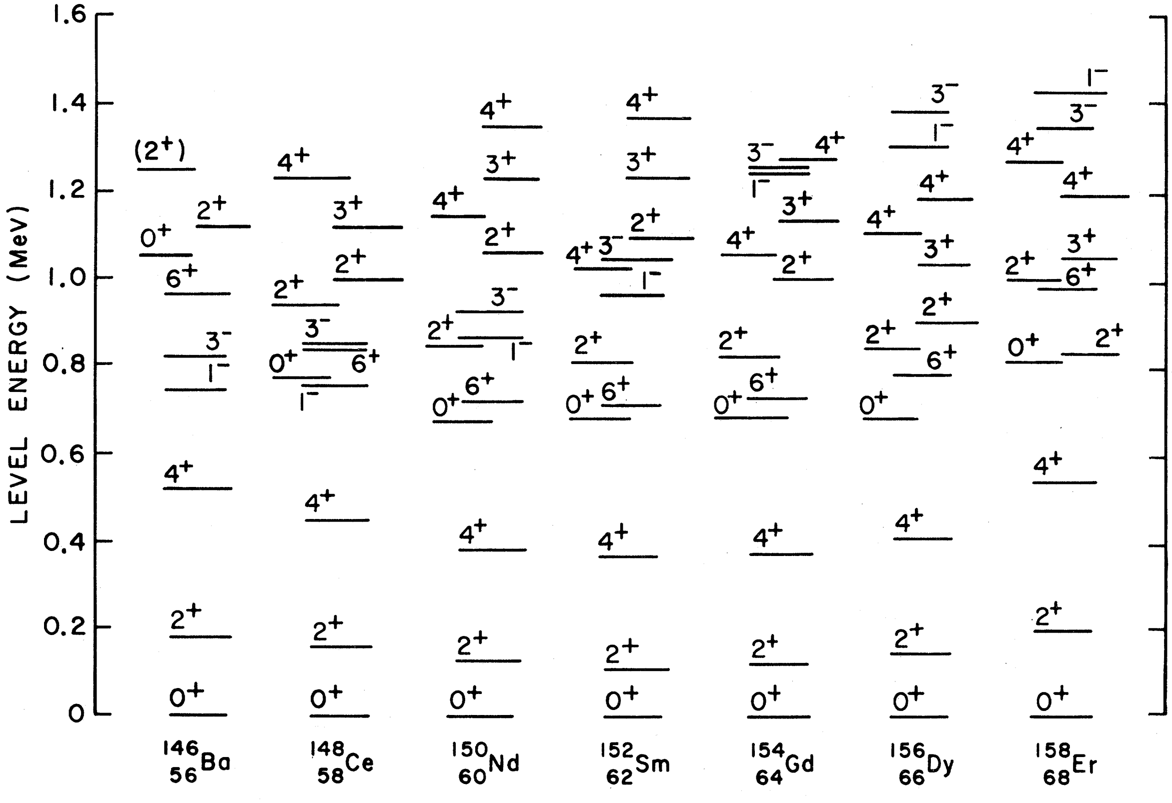

FIG. 7. The systematics of low lying levels in the $N=90$ isotones.

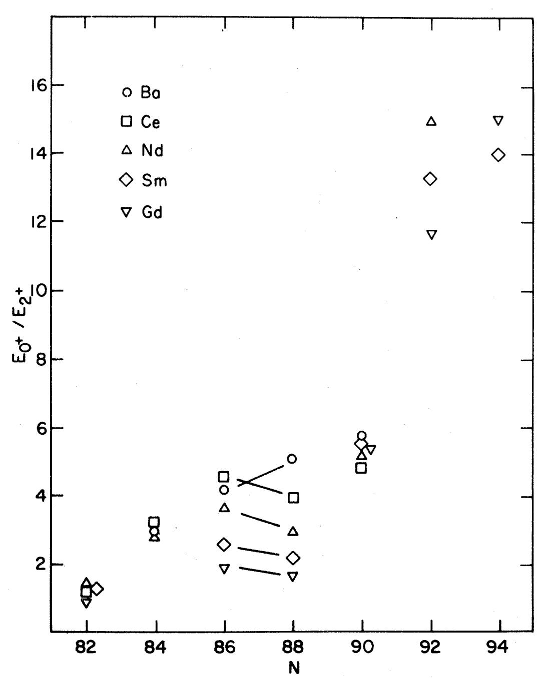

FIG. 8. The $E_{0_2^+}/E_{2_1^+}$ ratios for the light mass rare earth region.

for the Ce isotopes where the drop in the ratio at $N=88$ is less severe. Unfortunately, data are not available beyond $N=90$ for Ba and Ce so it is not known if a sharp increase occurs for higher N, as is found for the heavier isotones.

B. IBA calculations

Level energies for the Ce isotopes in this region have been calculated using the neutron-proton interacting boson approximation (IBA-2) with modified parameters that reflect the subshell closure at $Z=64$. The details and justification of the approach and the parametrization have been discussed elsewhere,[29] but, except for ^{146}Ce, the results for the Ce isotopes have not been presented. Therefore, it is our intention to present the results of the level energy and $B(E2)$ calculations in this subsection. Briefly, the calculations take the effects of the proton subshell closure at $Z=64$ into account by truncating the boson valence space for neutron numbers where there is empirical evidence for such a truncation.[30] The truncation simply involved redefining the extent of the proton shell closures: A shell from $Z=50$–64 for $84 \le N \le 88$, and a shell from $Z=50$–82 for $N \ge 90$ were used to predict the variation of the model parameters. The neutron shell closures were assumed to be unaffected by the $Z=64$ subshell closure.

Thus, redefining the proton shell closure primarily affects the parameters κ, χ_ν, and χ_π. Previous calculations[31] were unable to give good energy level fits while adhering to the microscopic predictions of the model parameter variations. In the calculations presented here, ϵ and κ were adjusted to give a good fit to the level energies for a particular nucleus ($^{148}_{62}Sm_{86}$), from which the normalization κ_0 for the $Z=50-64$ subshell was taken. χ_ν was given an arbitrary normalization and χ_π was varied as a free parameter. The values of κ and χ_ν for other nuclei in the $Z=50-64$ subshell were then calculated using the above prescription. The same procedure was adopted for the $Z=50-82$ shell (for $N\geq 90$) using $^{154}_{62}Sm_{92}$ as the nucleus from which the parameters were extrapolated. The results showed significant improvement, in agreement with experimental energy levels over previous calculations,[31] while yielding the parameter dependence predicted by the microscopic basis of the IBA-2 model. The calculations also showed that the level energies were only weakly dependent on the value of χ_π. The results of these calculations for ^{144}Ce, ^{146}Ce, and ^{148}Ce are shown in Fig. 9 for the first three members of the three lowest energy bands. ^{142}Ce has not been calculated since there are too few valence particles to reasonably justify the collective approach of the IBA.

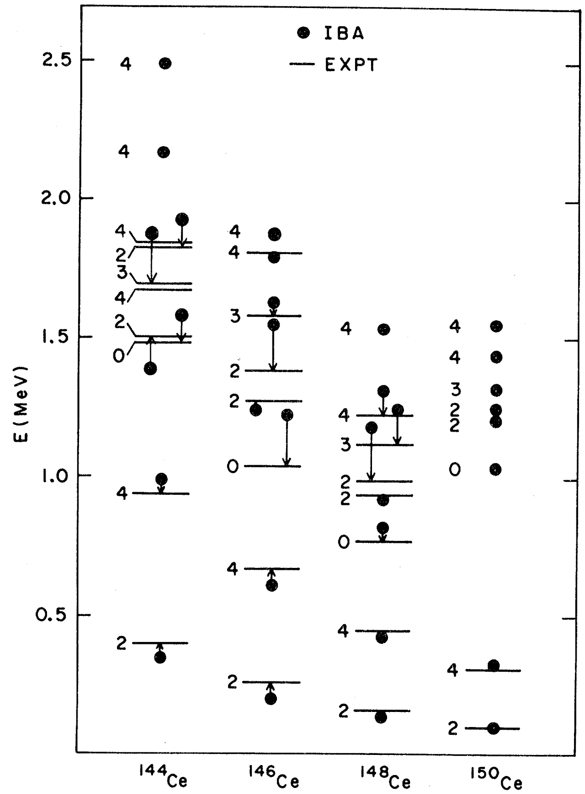

FIG. 9. Comparison of experimentally determined low lying levels in Ce isotopes with IBA-2 calculations. The dots represent the calculated values with arrows drawn to the corresponding experimental levels. A dot without an arrow or not lying on a line indicates that the level has not yet been determined experimentally.

The parameters that gave the best set of energy levels were used to calculate $B(E2)$ ratios. The results are shown in Table IV, where they are compared to experimental values and the predictions of the Alaga rules. It is evident that neither the Alaga rules nor the IBA calculations give good agreement with the data. The agreement between the experiment and the IBA-2 calculations is improved if χ_π is forced to be considerably more negative than the value (-0.95) used to obtain the energy levels shown in Fig. 9. The last column in Table IV shows the results when $\chi_\pi=-1.7$ is used. However, the energy levels obtained with this value of χ_π are in poor agreement with the experimental energies. The ground band is calculated too low by about 60 keV, while the excited bands are calculated too high by about 200 keV. Thus the model predicts that a more rotational structure is necessary to reproduce the observed $B(E2)$ ratios.

TABLE IV. $B(E2)$ ratio compared with predictions of the IBA-2 and the Alaga rules (Ref. 32).

Transitions[a]	Expt.	Alaga rules	IBA-2 $\chi_\pi=-0.95$	IBA-2 $\chi_\pi=-1.7$
$\frac{3'\to 4}{3'\to 2}$	2.39(9)	0.40	1.48	0.833
$\frac{2'\to 2}{2'\to 4}$	1.16(14)	19.07	6×10^{-5}	0.756
$\frac{2'\to 2}{2'\to 0}$	1.32(8)	1.43	3×10^{-4}	0.691
$\frac{2'\to 0}{2'\to 4}$	0.87(10)	13.3	0.19	1.10
$\frac{2''\to 2}{2''\to 4}$	0.70(11)	0.56	40.0	0.625
$\frac{2''\to 2}{2''\to 0}$	>83.3	1.43	8.47	18.4
$\frac{2''\to 2}{2''\to 0}$	<0.8	1.10	0.009	0.022

[a]Single primes denote γ band, double primes the β band, and absence of prime the ground band.

V. CONCLUSIONS

We have extended considerably the level scheme of ^{148}Ce. The unambiguous identification of J^{π} of many of the excited states was not possible in the angular correlation experiments due to the low counting rate available. However, the systematics and the deexcitation pattern, taken together, provide reasonable evidence in support of our preferred spin and parity assignments.

The half-life determined for ^{148}La (1.05 s) differs from the value of 1.2 s reported in the literature.[5] This discrepancy may be due to a β-decaying isomeric state in ^{148}La. However, there is no firm experimental evidence to support such a conclusion.

The IBA-2 calculations using a set of parameters which exhibit the microscopically predicted behavior give better agreement with experimental levels for the Ce isotopes within the model space than previous calculations,[31] but fail to calculate the proper transition rates for ^{148}Ce. This set of IBA-2 calculations (Fig. 9) predicts that the 0_2^+ state will increase in energy for ^{150}Ce. The predicted energy of 1040 keV is consistent with other $N=92$ isotones and would signal the beginning of clearly rotational structure for heavy Ce isotopes, if such behavior can be confirmed by experiment.

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