BAND STRUCTURE IN ^{148}Ce FROM THE DECAY OF MASS SEPARATED ^{148}La

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Abstract

The β decay of ^{148}La to levels in ^{148}Ce has been studied at the TRISTAN ISOL facility at Brookhaven National Laboratory's High Flux Beam Reactor. A level scheme for ^{148}Ce is presented which identifies a first excited 0^+ state at 770.16 keV. 0^+, 2^+ and 4^+ members of the ground state band, as well as 0^+_β, 2^+_β, 4^+_β, 2^+_γ, 3^+_γ and the 1^- and 3^- members of an octupole band are identified. IBA-2 calculations for the N=90 isotones and Z=58 isotopes are presented.

1. Introduction

The rare earth region of deformed nuclei has been studied very extensively in the past three decades. The investigations provided unusually complete knowledge of these isotopes and revealed impressive examples of smooth systematics of nuclear properties over a wide range of masses. Yet, there are parts of this region where information is still scarce. Thus the nuclei with nuclear charge Z=56-58 have been studied only partially. This is because these isotopes are not easy to access experimentally. They are neutron rich, and many have very short half-lives and can at present only be produced in nuclear fission. Efficient separation techniques are needed for these investigations. Recently the level schemes of even Ba isotopes (Z=56) were studied.[1)] Evidence was found that the onset of deformation occurs at lower neutron numbers in Ba than for isotopes with higher Z (Nd, Sm, Gd...) where it is known to be situated at N=90. Now, the separator TRISTAN[2,3,4)] at the High Flux Beam Reactor (HFBR) of the Brookhaven National Laboratory offers the possibility of studying the very neutron rich Ce isotopes through the β decay of their La parents. The investigation of ^{148}Ce, which is discussed here, was undertaken in order to establish the low-lying levels of this isotope and thus to complete the systematics of the N=90 isotones. In particular, it was of interest to ascertain whether deformation begins at N=90 as in the heavier isotones or at N=88 as in Ba.

Prior to the present investigation information has been published on the half-life of ^{148}La and on a few gamma transitions in ^{148}Ce. For the half-life of the β decay of ^{148}La values of $t_{1/2} = 1.29 \pm 0.08$ sec, $t_{1/2} = 1.7 \pm 0.5$ sec and $t_{1/2} = 2.61 \pm 0.61$ sec have been reported.[5)] Gamma transitions of 386, 295 and 159 keV have been attributed to ^{148}Ce as transitions between the 6^+, 4^+, 2^+ and 0^+ members of the ground state band.[5)] Very little is known about further levels. There was evidence for two additional gamma transitions of 379 and 538 keV[6)] which were supposed to depopulate a 2^+_2 level at 538 keV.

2. Experimental Techniques

2.1 TRISTAN

The TRISTAN isotope separator facility 2,3,4,7) is installed at an external beam tube of the HFBR. For the studies of the La decays a Surface Ionization Source[8)] was implemented into the system. About 5g of highly enriched ^{235}U are impregnated into a graphite cloth cylinder. The cylinder of 3 cm length and 2 cm diameter is exposed to a flux of about 1.5×10^{10} neutrons per cm^2 per sec. The target is located inside the ion source and is heated by electron bombardment to approximately 2200°C. The fission products are evaporated from the cylinder and ionized on a Re surface. They are separated according to their mass through a 90° magnet and focussed onto a moving tape collector.

2.2 Gamma-ray Measurements

Gamma-ray singles spectra were taken at the place where the fission products are deposited onto the tape (the parent port). The tape was moved every 4 sec in order to suppress the radiation from long-lived A=148 isobars. In a separate experiment, gamma-ray spectra were registered in the multiscaling mode. The ion beam was deposited for 3 sec and then the beam was shut off for 4 sec while 32 spectra were taken during time intervals of 0.125 sec. Afterwards the tape was moved 15 cm and then the cycle was repeated. The multiscaling measurements enabled determination of the half-life for the β decay of ^{148}La, the assignment of gamma transitions to this decay and the reduction of the activity of the shorter lived precursors of ^{148}La. The detectors were positioned 180° apart at the parent port during the γ-γ coincidence measurements. Both detectors were positioned 1 cm from the source which formed a line of 1 mm width and 5 mm height. The addresses derived from the energy signals and the time relationship between responses from both detectors were stored in event-by-event mode on magnetic tape.

2.3 Beta Measurements

A short, 12 hr, β spectrum was accumulated using a thin hyperpure Ge detector with an 12 μm Ti window. This detector has high efficiency for electrons up to 10 MeV and views the source with an overall solid angle of about 4% of 4π. The energy shift due to window losses (8.25 keV) was determined by counting an uncovered ^{207}Bi source. A singles spectrum of ^{148}La was taken at the parent port with the tape moving at 5 sec intervals. The experiment was performed for the explicit purpose of identifying E0 electron transitions.

3. Results

3.1 Gamma Intensities and Half-life

The information on the energies and the relative intensities of the gamma transitions in ^{148}Ce is compiled in Table 1. The intensities take into account the energy dependence of the efficiency of the detectors, but they are not corrected for internal conversion. They are normalized to 1000 units for the 158.40 keV transition from the first excited 2^+ level into the ground state. It is obvious that all gamma transitions are much weaker than this line which is the main reason for the limited information on the level scheme of ^{148}Ce up to now. Gamma transitions with intensities as low as 6 relative units were observed in the present study. Analysis of the multispectra data yielded a value of 1.19 ± 0.05 sec for the half-life of ^{148}La.

Table 1. List of energies (in keV) and intensities of the γ transitions in ^{148}Ce.

E_γ (keV)	I_γ	E_γ (keV)	I_γ
158.40± 0.05	1000± 20	831.33± 0.02	93± 5
252.38±0.03	30±2	887.13±0.10	8±1
256.52±0.17	6±1	921.32±0.12	10±2
294.93±0.07	120±1	958.25±0.02	71±1
298.30±0.31	13±1	967.40±0.35	7±2
369.32±0.06	12±1	989.87±0.01	168±5
378.98±0.03	71±1	1105.07±0.14	6±1
387.79±0.08	25±1	1130.95±0.08	19±2
425.60±0.09	18±1	1257.39±0.13	11±1
433.23±0.09	20±1	1298.41±0.25	15±1
482.12±0.04	17±1	1302.60±0.30	2±2
536.30±0.15	9±1	1316.54±0.16	8±1
601.83±0.02	137±2	1338.58±0.04	32±2
611.76±0.04	52±1	1425.49±0.08	16±1
654.49±0.09	14±4	1431.47±0.05	24±1
663.32±0.02	27±1	1464.13±0.10	16±1
682.93±0.02	116±9	1496.85±0.09	11±1
713.34±0.10	9±1	1569.56±0.18	7±2
760.28±0.01	154±7	1589.76±0.09	15±1
770.52±0.08	9±1	1732.41±0.13	12±1
777.15±0.01	129±2	1768.98±0.19	16±2
794.43±0.09	13±1	1890.53±0.07	22±1
819.28±0.06	24±6	1985.43±0.07	44±1
		1994.73±0.05	59±2
		2030.69±0.09	21±2
		2033.12±0.15	12±2
		2093.05±0.05	126±2
		2152.88±0.11	13±2
		2219.12±0.15	27±2
		2391.35±0.06	70±5
		2549.75±0.30	6±4

3.2 Level Scheme

The level scheme of ^{148}Ce is shown in fig. 1. It has been constructed from the coincidence information and the intensities have been corrected for internal conversion where possible. Since most of the levels are depopulated through more than one gamma transition their energies are well established. Only 3 of the gamma lines of Table 1 are not incorporated into the scheme. The β feedings and the log ft values have been calculated from the relative gamma intensities including internal conversion. They do not take into consideration a possible β transition into the ground state of ^{148}Ce or unobserved gamma feedings of the levels through high energy transitions from high lying levels.[9] The fact that the probable 0_2^+-level is only weakly fed in the β decay suggests that the ground state feeding should not be strong.

3.3 Ground State Band

The 2_1^+ and 4_1^+ levels which were identified previously are confirmed. No population of the 6^+ level has been observed in the present investigations. The level at 841.23 keV is not identical with the 6^+ level, the energy of which has been reported to be 840.9 keV. The energy difference is beyond the experimental uncertainties and the deexcitation excludes spin 6 for the level observed. A level at 537 keV in ^{148}Ce 6) could not be confirmed. The coincidence data require a different position of the gamma rays which were supposed to deexcite this state.

4. Discussion

Information on the nature of the low lying levels in ^{148}Ce is deduced from the gamma ray deexcitation pattern and from the systematics of the levels both of the lighter even Ce isotopes and of the N=90 isotones. The position of the first excited 0^+ level (0_2^+) is of special interest for the understanding of nuclear structure. It is well known that inside a series of isotopes the 0_2^+ level lies lowest at the onset of deformation. In the vibrational light isotopes the 0_2^+ state belongs to the two-phonon triplet and lies high. In the deformed region it forms the head of the β band and again has a higher energy.

4.1 0_2^+ State

The lowest candidate for the 0_2^+-state in ^{148}Ce is the level at 770.16 keV. All other new levels below 1300 keV are depopulated either into the ground state or into the 4_1^+ level. Those gamma transitions would be strictly forbidden or highly improbable from a 0^+ level. There is a gamma ray (770.52 keV) which could suggest a crossover transition from the 770.16 keV level to the ground state. However, this gamma ray is observed in coincidence with the 294.93 keV (4_1^+ to 2_1^+) and the 158.40 (2_1^+ to 0_1^+) transitions. Therefore it cannot depopulate the level at 770.16 keV. The β spectrum from the experiment described in sect. 2 showed evidence for an E0 transition between the 770.16 keV level and the ground state. But due to background contamination

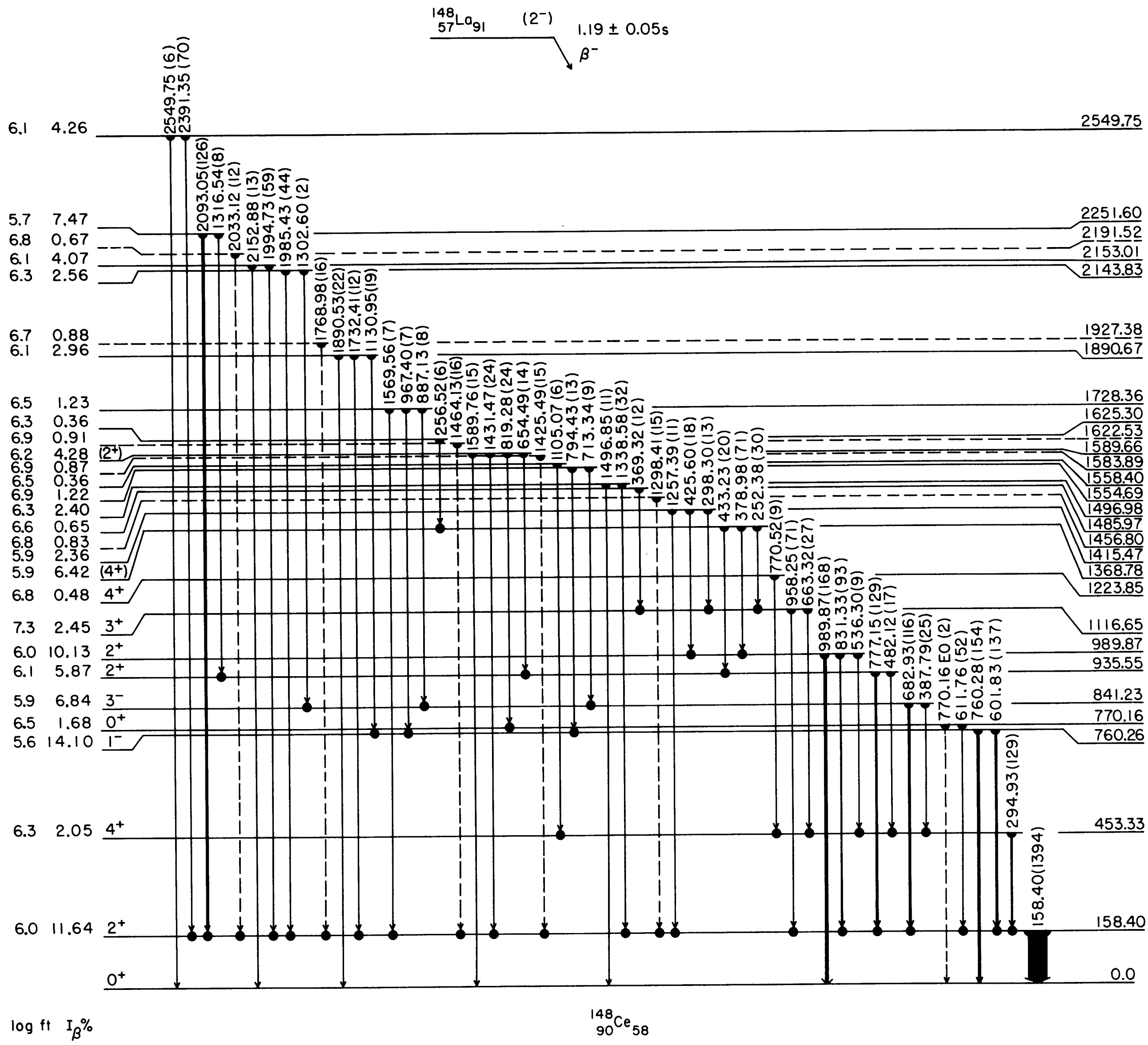

Fig. 1 The proposed level scheme of ^{148}Ce. The placement of all transitions is established through coincidence results.

from a previous experiment, the electron line was not completely resolved. An upper limit for the E0 transition from the 770.16 keV level was placed at 3 percent of the total depopulation of that level.

Hence, based on its depopulation, the tentative observation of the E0 line and N=90 isotone systematics, fig. 2, it is supposed that the level at 770.16 keV is a 0^+ state. Its interpretation as the first excited 0^+-level in ^{148}Ce is suggested by the systematics of the N=90 isotones and the failure to observe other E0 lines in the β spectrum.

4.2 Octupole Band

Both the systematics of the Ce isotopes, fig. 3, and of the N=90 isotones predict the 1^- and 3^- levels around 500 to 1000 keV excitation energy. Good candidates for these levels are the states at 760.26 and 841.23 keV respectively. This assignment is also supported by the deexcitation pattern of these levels.

4.3 Beta Band

If the 0^+_2-level is supposed to lie at 770.16 keV then it is very likely that the state at 935.55 keV is the 2^+ member of the β band. The systematics, figs. 2 and 3, support this choice. In the other N=90 isotones the difference in energy between the 2^+_β and 0^+_β level is approximately equal to the excitation energy of the 2^+_1 state. The 2^+_β assignment of the 935.55 keV level would give 165.39 keV for the 2^+_β-0^+_β difference in ^{148}Ce compared to 158.40 keV for the energy of the 2^+_1 level. The fact that no transition from the 935.55 keV level

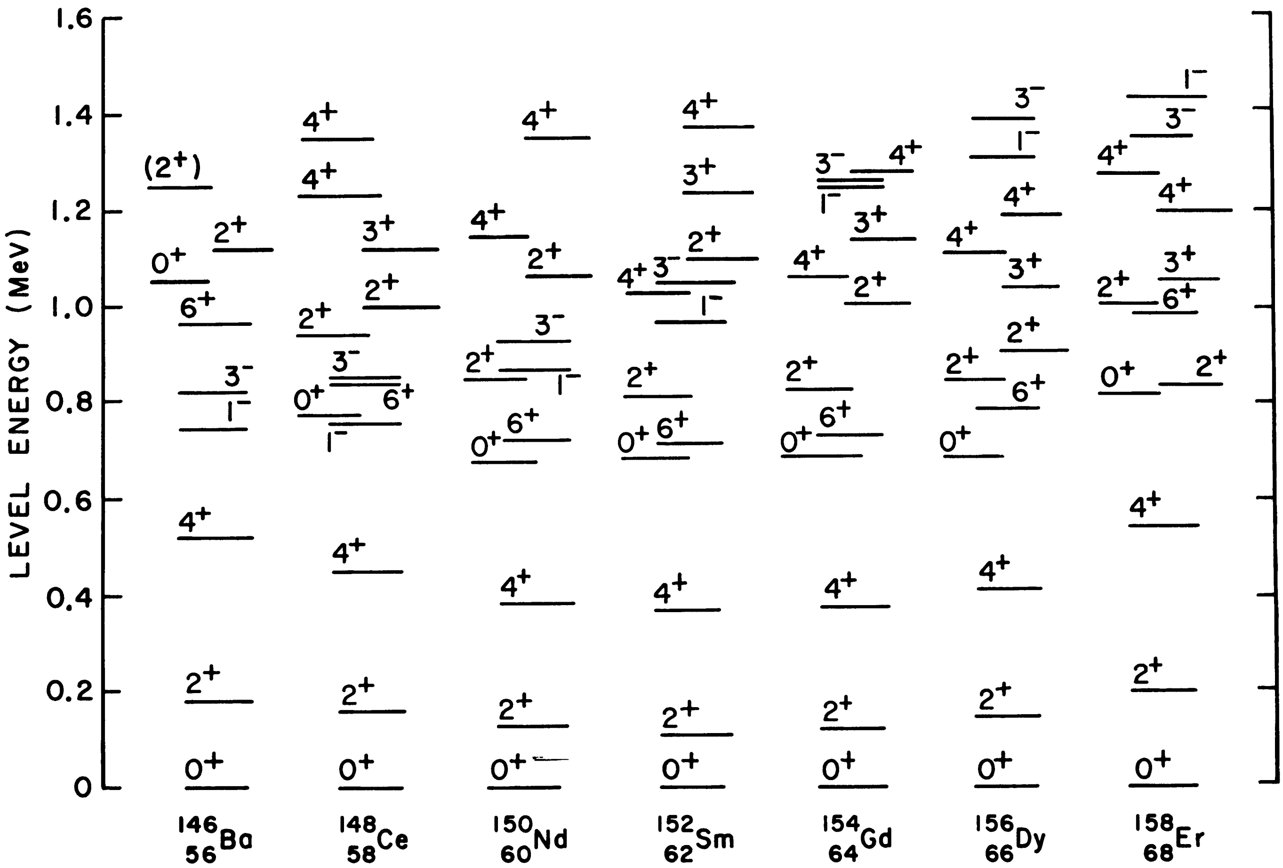

Fig. 2 The systematics of the N=90 isotones.

into the ground state or the 0_β^+ state has been observed is in line with the generally weak 2_β^+ to 0_1^+ and 2_β^+ to 0_β^+ transitions in the isotones.

A good candidate for the 4^+ state of the β band is the level at 1223.85 keV. With this assignment the ratio of the 4_β^+ level over that of the 4_1^+ level 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 in reasonable agreement with the situation in the heavier isotones.

4.4 Gamma Band

The level at 989.87 keV is considered as the 2^+ head of the γ band because of its deexcitation which connects it with the ground state, the 2_1^+ state and the 4_1^+ state. The 3^+ level of this band might be the state at 1116.65 keV. The difference between 1116.65 and 989.87 keV is very similar to the difference of the 3_γ^+ and 2_γ^+ levels in ^{152}Sm and ^{154}Gd. Higher spin members of the γ band are not obvious among the observed levels in ^{148}Ce.

4.5 Systematic Trends

Although the above-mentioned spin and parity assignments are by all means tentative, they form a best choice at the present state of knowledge about the level scheme of ^{148}Ce. A different grouping of the levels would lead to irregularities in the systematics. With the proposed assignments the systematics are very smooth. This is especially true for the ground state and β band as well as for the 1^- and 3^- levels. The β band follows the tendency of the ground state band which have the lowest lying members at ^{152}Sm and ^{154}Gd. The γ band reveals less regularity since there is a rise of the 2_3^+ level between ^{148}Ce and ^{146}Ba.

The trends of the levels in the Ce isotopes make it clear that the onset of deformation cannot be considered to take place earlier than N=90. All relevant levels decrease strongly between ^{146}Ce and ^{148}Ce in contrast to the situation for ^{144}Ba and ^{146}Ba. This was known for the ground state band; it has been shown in the present work for the other low lying states. Especially the energies of the lowest observed 0^+ levels decrease strongly between ^{146}Ce and ^{148}Ce. If these levels are indeed the 0_2^+ states then they can have their minimum at ^{148}Ce at the earliest.

It is of interest to inspect the ratios of the energies of the 0_2^+ levels over the energies of the 2_1^+ states. These ratios are plotted in fig. 4. They are considered as a clear indication of the onset of deformation.[10] For the Nd, Sm and Gd isotopes they stay around 2 in the vibrational area and then rise sharply at N=90 to values above 10. The situation is different

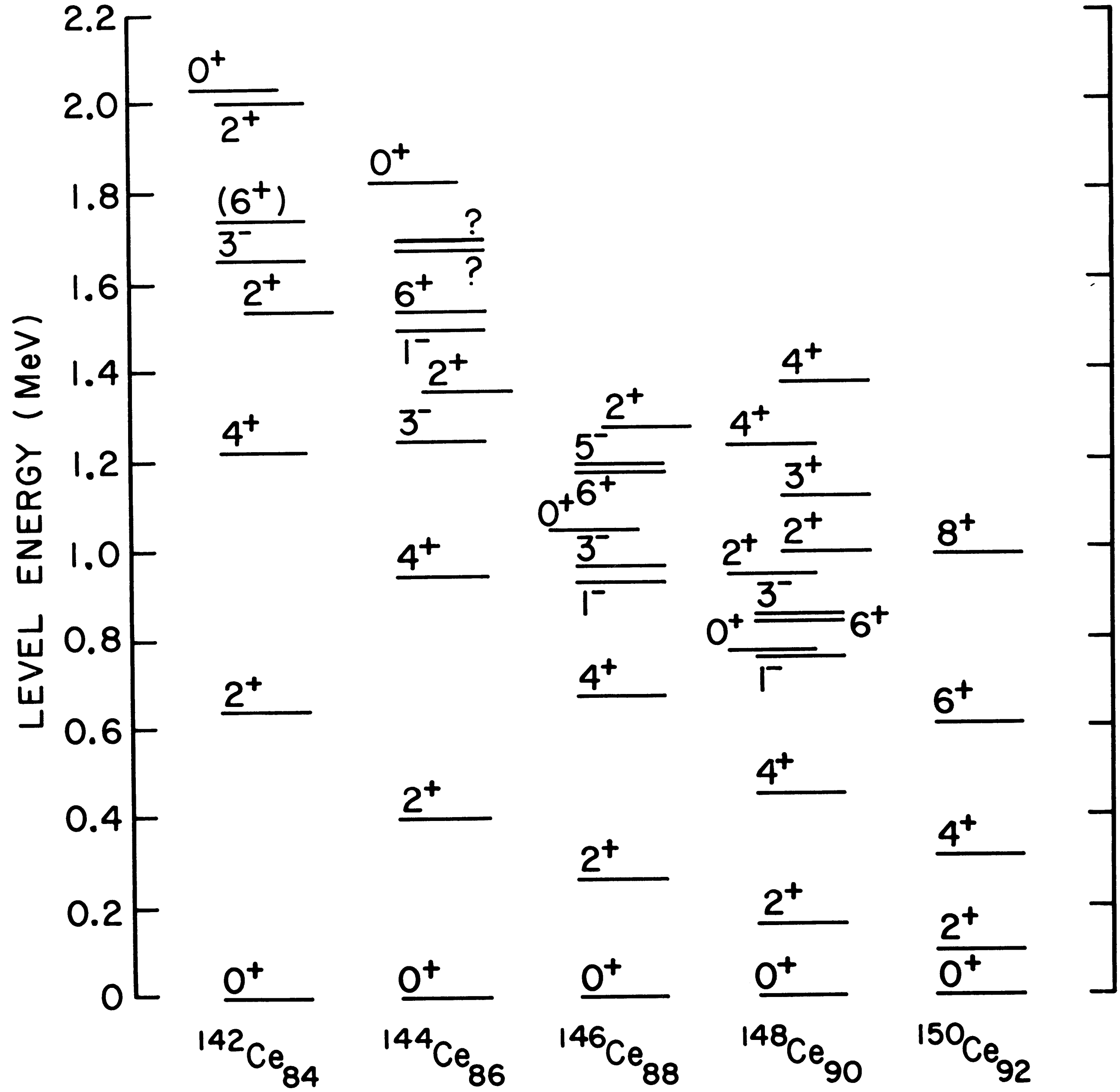

Fig. 3 The systematics of the Z=58 isotopes.

for Ba as to the present knowledge.[1] Here the ratio rises continuously which can be an indication of a more gradual change of nuclear shapes. The investigations at TRISTAN show an intermediate situation for the Ce isotopes.

4.6 IBA Calculations

Prior to the experimental studies on the level scheme of ^{148}Ce calculations using the Interacting Boson Approximation Model were performed for this nucleus. The parameters for the Hamiltonian of IBA-2 have been determined by detailed fits to isotopes and isotones of ^{148}Ce to produce values for χ_π and χ_ν respectively. Values for the boson energy, ε, and the quadrupole interaction strength, κ, have been determined by requiring the 2_1^+ and 4_1^+ energies (which were previously known) to be calculated exactly. No other parameters were allowed to vary. When the results of this calculation are compared to the experimental data, the agreement is good which supports the proposed identification of the observed low lying levels in ^{148}Ce.

Figure 5 shows a comparison of IBA-2 calculations with experiment for the low lying levels of the N=90 isotones. The IBA-2 results for Nd, Sm and Gd were obtained using parameters given in 11). The experimental points are from ref. 5). Figure 6 shows a similar comparison for the Ce (Z=58) isotopes. The IBA-2 model is not expected to work well too near a closed shell and the calculations do show considerable discrepancy for the Ce isotopes near N=82. However, as N gets larger, the agreement improves. In any case, the model does predict the correct trends in the systematics, except for the 2_2^+ state in ^{142}Ce.

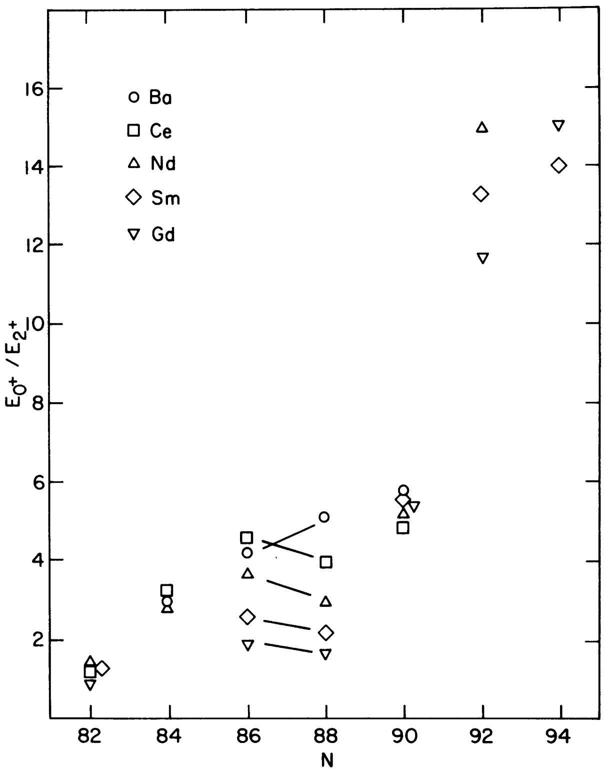

Fig. 4 The $E0_2^+/E2_1^+$ ratios for the rare earth region.

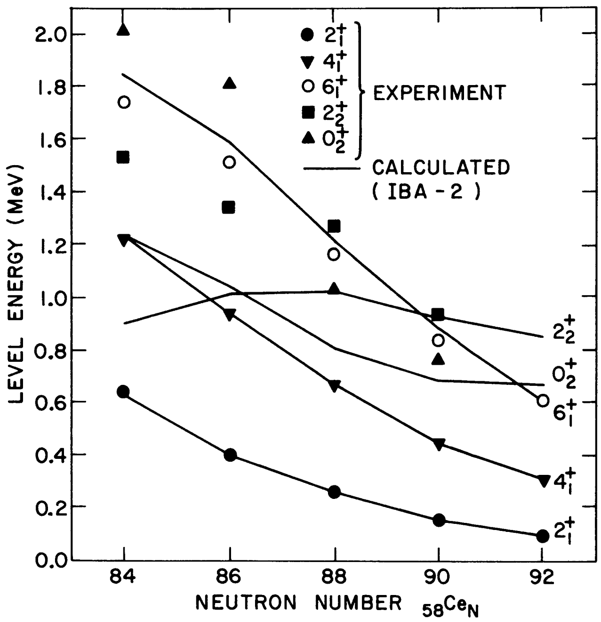

Fig. 6 Comparison of IBA-2 calculations (solid line) with experimental data for low lying levels in the Z=58 isotopes.

5. Conclusions

The level scheme of ^{148}Ce has been extended considerably. Although the low intensities of the transitions prohibited the unambiguous experimental identification of the levels, the systematics and the

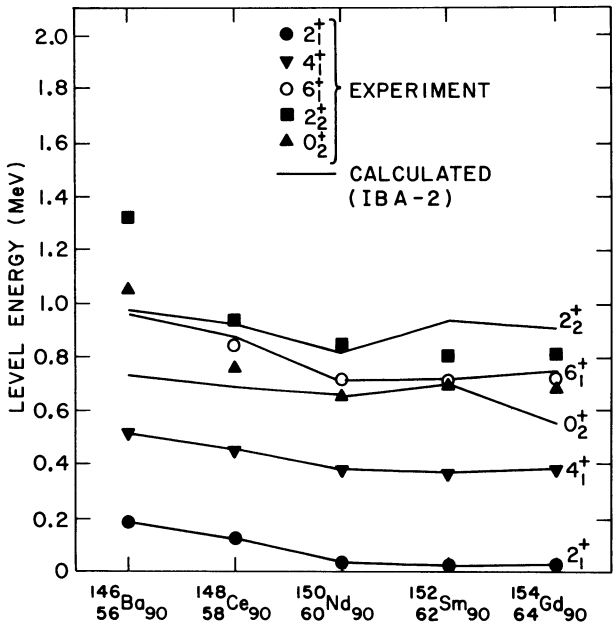

Fig. 5 Comparison of IBA-2 calculations (solid line) with experimental data for low lying levels in the N=90 isotones.

deexcitation pattern suggest spin and parity assignments. All evidence shows that the onset of deformation in the Ce isotopes does not take place prior to N=90 in contrast to the situation in Ba. The reported value of the deformation parameter β_2=0.25, the $E_{4_1^+}/E_{2_1^+}$ ratio of 2.86 and the $E_{0_2^+}/E_{2_1^+}$ ratio of 4.9 indicate that ^{148}Ce is deformed but still in the transition to a classical rotor. The comparison with the IBA-2 calculations demonstrates the predictive power of this model.

The determination of the half-life of ^{148}La confirms the published value of 1.2 sec. There is no unambiguous evidence for the existence of a β-decaying isomeric state in ^{148}La while in ^{146}La isomerism has been observed. Most of the β feedings of fig. 1 can be accounted for if ^{148}La has a spin of 2^-. The feedings of the proposed 0^+ and 4^+ levels in ^{148}Ce may indicate the presence of another isomer, but the magnitude of the feedings must be considered cautiously since they are based on gamma-ray intensity balances.

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