LEVELS IN ^{146}Ce AND THE N=88 ISOTONES*

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Abstract

An investigation of the level structure of ^{146}Ce following the beta decay of the low-spin isomer of ^{146}La has been carried out at the ISOL facility TRISTAN at Brookhaven National Laboratory. The half-life for the low spin isomer was found to be 6.0 $\pm$ 0.4s. A partial level scheme for ^{146}Ce below 2 MeV is given. The level energies and some B(E2) values extracted from our data have been compared with IBA-2 calculations done entirely with extrapolated parameters from neighboring Z nuclei in order to check the predictive power of the model. Systematics of the Z=58 isotopes and N=88 isotones indicate that although ^{146}Ce is more deformed than its isotones with Z$\geq$60, the transition to the well-deformed region can probably more correctly be thought to occur after ^{146}Ce, between N=88 and N=90, as it does for Z$\geq$60. The abrupt onset of deformation present in the higher Z isotopes is not seen in the Ce isotopes where the trend is found to be rather smooth throughout.

1. Introduction

The onset of deformation in the rare earth region for Z$\geq$60 has been well known for many years to occur between N=88 and N=90 where the transition from the near spherical to the aligned coupling scheme appears to occur rather abruptly. The lower nuclear charge (Z$\leq$58) members of this transitional region of rare earth nuclei have not been studied previously in any great detail. Little was known of the effect of the lower nuclear charge on the deformation until recently when studies of the heavy Ba (Z=56) isotopes[1] were undertaken. This investigation yielded evidence that the transition to the well-deformed region already occurred for the N=88 nucleus ^{144}Ba, unlike the case for the known higher-Z nuclei. Recently a study of the heavy Ce (Z=58) isotopes in this region has been undertaken[2-4] at the TRISTAN[5] mass-separator facility which operates on line with the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL). This study is primarily concerned with the investigation of the low-lying level structure of the pivotal N=88 nucleus, ^{146}Ce, produced in the β decay of ^{146}La. Comparisons of experimental level energies and B(E2) transition probabilities with IBA-2 calculations are presented. Systematic comparisons among the N=88 isotones and Z=58 isotopes are also made. Of particular interest is the determination of the onset of deformation for the Ce isotopes, specifically whether it occurs between N=88 and N=90 as for Z$\geq$60 or earlier as it does in Ba.

Previous studies have given a variety of inconclusive information on the isomer and half life situation in ^{146}La. Skarnemark et al.[6] in a chemical separation study have reported two isomers for this isotope with half lives of 8.5s and 4.5m. Recent studies with on-line mass separators[7] indicate 6.2s and 10.0s isomers instead of the 8.5s isomer of Skarnemark. Earlier only one state with an 11s half life was reported[8] for ^{146}La. Very little previous information exists on the level properties of ^{146}Ce. Levels at 1172, 668 and 258 keV have been assigned to be the 6^+, 4^+ and 2^+ members of the ground state band.[8] In addition, levels at 925, 961, 1043 and 1183 have tentatively been assigned[6] to be 2^+, 3^-, 1^- or 2^+, and 3^-, respectively. Another study[9] assigns the 1183 keV level a spin-parity of 5^- and a level at 1551 keV to be 7^-. Seven additional levels have been proposed and 24 gamma rays placed in the most complete level scheme previously known.[6]

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2. Experimental Techniques

The ^{146}Ce activities of interest for this work were obtained as mass-separated fission fragments from the ISOL facility TRISTAN[5] on-line to the HFBR at BNL. Ion beams of Cs and Ba isotopes were directly produced by a surface ionization integrated target-ion source system.[10] These beams were then separated by mass and deposited on a moving tape collector system where the desired activities were counted and recorded by various detector analyzer systems.[5] The implanted ions were time-sequenced by the moving tape to optimize the desired activity.

No direct production of the desired ^{146}La parent was observed in our experiments. In this case ^{146}La is produced only following the β decay of even-even ^{146}Ba. Singles spectra (both low [<2 MeV] and high [up to 7 MeV]) and γγt coincidence data (low-low and low-high energy ranges) were taken at the point of deposition on the tape collector with hyperpure gamma-X and 20% Ge(Li) detectors in order to study ^{146}Ba and ^{146}La decays simultaneously. The activities were gathered and transported every 16s in order to avoid buildup of contaminating longer-lived A=146 isobars. The high-low coincidences were taken with 1/4" Pb on the high energy side to remove many of the contaminating low-energy ^{146}Ba events. In addition, gamma spectrum multiscaling and three angle (90°, 130° and 180°) γγ(θ) angular correlations were taken with the same two detectors at a detection station 60 cm from the point of deposition. Mass 146 ions were collected for 8 (or 16)s, moved 30 cm to an intermediate point for 8 (or 16)s to allow the ^{146}Cs and ^{146}Ba to decay into the La, and then transported another 30 cm to the detection station for 8 (or 16)s of counting.

3. Experimental Results and Discussion

Gamma spectrum multiscaling measurements on a number of strong lines attributed to the decay of ^{146}La yield only a single half life, 6.0 ± 0.4s. In our experiments, ^{146}La is only produced following the β decay of even-even ^{146}Ba. Thus only the low-spin isomer of ^{146}La is populated from the 0^+ ground state of its Ba parent. The 6.0s half life found in our work agrees well with the 6.2s half life previously reported[7] for the low-spin isomer in ^{146}La, but disagrees with a half life of 8.5s proposed by Skarnemark[6] as the only short-lived state of ^{146}La.

Forty-five levels (and over 150 γ rays) up to ∿5 MeV and 30 levels (and 90 γ rays) below 2.5 MeV have been established for ^{146}Ce from extensive sets of coincidence relationships studied (>4x10^7 events recorded in the ^{146}La-enhanced high-low γγt experiment alone). Table 1 lists the γ rays observed connecting levels below 2 MeV. Information on the nature of the low-lying levels in ^{146}Ce was deduced from the γ ray deexcitation patterns, systematic trends of the levels of the lighter even Ce isotopes and surrounding N=88 isotones, and angular correlation measurements. The possible spin parity assignments for these

Table 1

Gamma rays observed following the decay of low-spin ^{146}La to levels in ^{146}Ce. The γ lines given are those assigned as transitions connecting two (or more) levels below 2 MeV.

E_γ (keV)*	I_γ*,†	Transition $E_i \rightarrow E_f$
^{c} 36.2(3)	1.7(10)	961→ 925
^{c} 107.6(5)?	0.15(15)	1382→1274
^{c} 118.6(3)	1.2(5)	1043→ 925
^{c} 194.8(5)?	0.52(25)	1577→1382
^{c} 231.2(5)	0.73(30)	1274→1043
258.47(6)	1000	258→ 0
^{c} 275.5(3)?	0.64(30)	1657→1382
292.4(1)	11(1)	961→ 668
^{c} 302.4(3)?	0.32(20)	1577→1274
313.5(1)	2.6(3)	1274→ 961
^{c} 338.8(3)	0.48(15)	1382→1043
349.7(2)	3.0(3)	1274→ 925
^{c} 383.1(3)	0.91(35)	1657→1274
409.85(6)	70(5)	668→ 258
421.1(1)	5.4(4)	1382→ 961
457.3(1)	12(1)	1382→ 925
502.9(1)	5.4(5)	1171→ 668
514.7(2)	6.7(3)	1183→ 668
533.7(2)	1.8(3)	1808→1274
^{c} 607.1(4)	1.3(5)	1274→ 668
666.07(6)	98(5)	925→ 258
702.28(6)	100(5)	961→ 258
^{d} 713.5(5)	7.6(20)	1382→ 668
^{d} 713.5(5)	1.9(10)	1757→1043
784.66(6)	48(3)	1043→ 258
793.0(2)	15(1)	1754→ 961
829.3(2)	15(2)	1754→ 925
832.0(2)	6.8(8)	1757→ 925
908.2(2)	4.7(4)	1577→ 668
924.56(8)	123(6)	925→ 0
959.2(2)	4.0(5)	1628→ 668
1015.9(1)	52(3)	1274→ 258
1028.5(2)	3.7(4)	1989→ 961
1064.6(2)	7.6(5)	1989→ 925
1123.4(2)	6.5(5)	1382→ 258
1134.2(3)	2.9(4)	1802→ 668
1140.2(2)	6.1(5)	1808→ 668
1274.4(2)	20(2)	1274→ 0
1318.3(2)	19(2)	1577→ 258
1368.8(3)	1.7(5)	1628→ 258
1382.1(2)	27(2)	1382→ 0
1398.9(3)	7.0(6)	1657→ 258
1498.2(2)	22(2)	1757→ 258
1544.0(3)	6.1(6)	1802→ 258
1550.3(3)	6.1(6)	1808→ 258
1756.7(3)	12(1)	1757→ 0

*Errors given in parentheses are the uncertainties in the last number(s) reported, e.g. 12(1)≡12±1.

†Intensities are relative to the 258 keV γ ray ≡ 1000.

^{c}Intensity and energy determined from coincidence spectrum.

^{d}Doublet, actual energies of the two γ rays are estimated from coincidence measurements.

levels are given in Table 2. Figure 1 shows a partial level scheme for ^{146}Ce which includes all positive parity levels below 2 MeV. All levels in the figure are assigned a single most probable spin and parity.

The previously reported[8] 2^+, 4^+, 6^+ ground state band members have been confirmed in our measurements. Anisotropies

Table 2

Possible spin-parity assignments for levels of ^{146}Ce below 2 MeV.*

E_{level}	I^{π}	E_{level}	I^{π}
0	0^+	1381.9	2^+
258.5	2^+	1576.7	$3^+(2^+,3^-,4^+)$
668.3	4^+	1627.5	$2^+,3^{\pm},4^+$
924.6	$1^-(1^+,2^+)$	1657.4	0^+
960.8	$3^-(2^+,3^+,4^+)$	1753.8	$1^-,2^{\pm},3^-$
1043.1	0^+	1756.7	$1^{\pm},2^+$
1171.3	$6^+(2^+,3^{\pm},4^{\pm},5^{\pm})$	1802.5	$2^+,3^{\pm},4^+$
1183.1	$5^-(2^+,3^{\pm},4^{\pm},5^+,6^+)$	1808.4	$4^+(2^+,3^{\pm})$
1274.3	2^+	1989.2	$1^-,2^{\pm},3^-$

*Preferred assignments are listed first.

observed in the 785-258 and 1399-258 keV cascades from our $\gamma\gamma(\theta)$ angular correlation experiments[2,11] indicate that levels at 1043 and 1657 keV are good candidates for low-lying 0^+ levels in ^{146}Ce.

Assuming the level at 1043 keV is the 0_2^+ level and band head of the β band, then the state at 1274 keV is the most likely candidate for the 2^+ member of the band. The deexcitation of this level to both the 0_1^+ ground state and 4_1^+ level indicate a 2^+ spin-parity assignment for this level. In the systematics of the low lying (<2 MeV) levels for the N=88 isotones (Fig. 2), the $E2_{\beta}^+ - E0_{\beta}^+$ energy difference is approximately equal to or slightly less than the 2_1^+ state. The 231 keV difference in energy between the 1274 and 1043 keV levels compared with the 258 keV energy of the first excited 2^+ state is consistent with this pattern. A good candidate for the 4^+ member of the β band is the level at 1808 keV. This level follows the trends of the heavier N=88 isotones smoothly. In addition, there is a

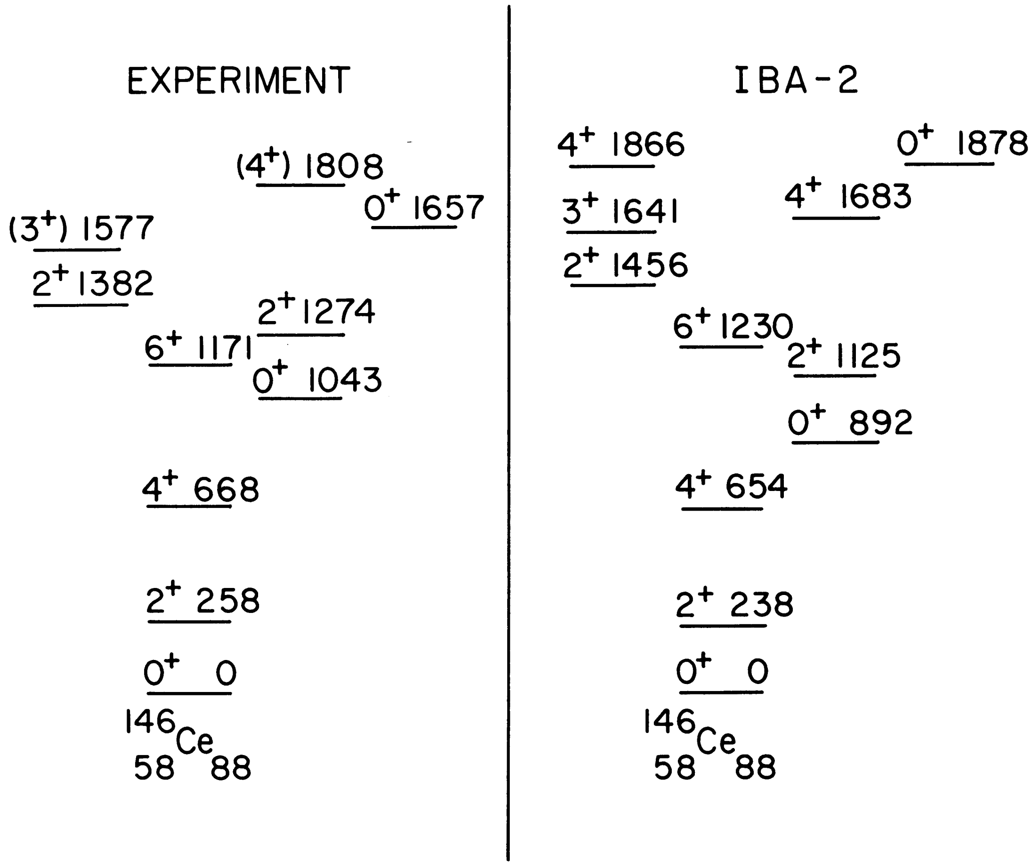

Fig. 1 Experimental positive parity levels below 2 MeV in ^{146}Ce and their comparison with values predicted by the IBA-2 model. Parameters used in this calculation: $\chi_{\pi}=1.2$, $\chi_{\nu}=-0.8$, $\kappa=-0.120$, $\varepsilon=0.65$.

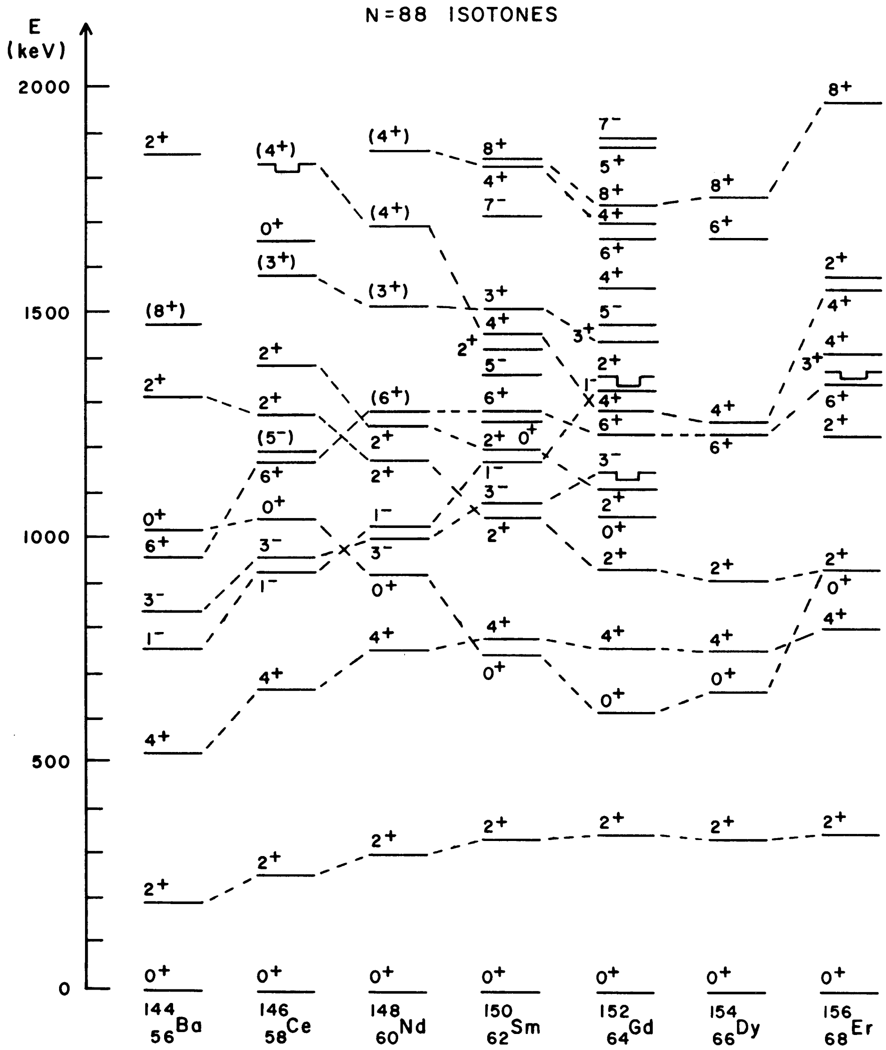

Fig. 2 Low-lying level systematics of the N=88 isotones. Dotted lines are drawn to guide the eye and are used to suggest related structures in successive isotones. The data used are taken from: ^{144}Ba,[1)] ^{146}Ce (present study), ^{148}Nd,[8,15)] ^{150}Sm,[8)] ^{152}Gd,[8)] ^{154}Dy,[8)] and ^{156}Er.[16)].

relatively large depopulation of this level to the 2^+ member of the β band. This strong intraband transition is another indication of the connection of this state with the β band.

The level at 1382 keV is assigned a spin-parity of 2^+ due to its deexcitation pattern of feeding both the 0^+ ground state and the 4_1^+ level. This level is assumed to be the band head of the γ band in ^{146}Ce. The level at 1577 is the best candidate for the 3^+ member of this band. The 1577-1382 keV level difference closely follows the trend observed for this difference from the heavier N=88 isotones. Higher spin members of the γ band are not obvious among the remaining low lying levels in ^{146}Ce.

The systematics of the N=88 isotones and Ce (Z=58) isotopes both predict the lowest lying negative parity states, 1^- and 3^-, to be between 800 and 1000 keV excitation energy. The most probable candidates for these states are the levels at 925 and 961 keV, respectively. This is supported by the coincidence/singles intensity ratios for the 925-258 keV and 961-258 keV transitions. These ratios are consistent with E1 multipolarities for the γ rays connecting these levels. Also the branching ratios for γ rays depopulating these negative parity levels agree reasonably well with the values from the other N=88 isotones. In addition, the angular correlation study yields results for these levels consistent with 1-2-0 and 3-2-0 spin sequences. The level at 1183 keV is possibly the 5^- member of the octupole band built on the 1^- and 3^- states. The 5^--3^- energy differences in the N=88 isotones ^{150}Sm and ^{152}Gd are found to be comparable to the corresponding 2^+ level energies. The difference of 223 keV between the proposed 5^- level and the 3^- level in ^{146}Ce is close to the 2_1^+ level energy of 258 keV, in agreement with the expected trend.

Despite the fact that the spin-parity assignments made for several of the levels in ^{146}Ce are tentative, they are the best choice based on the known data. Changing

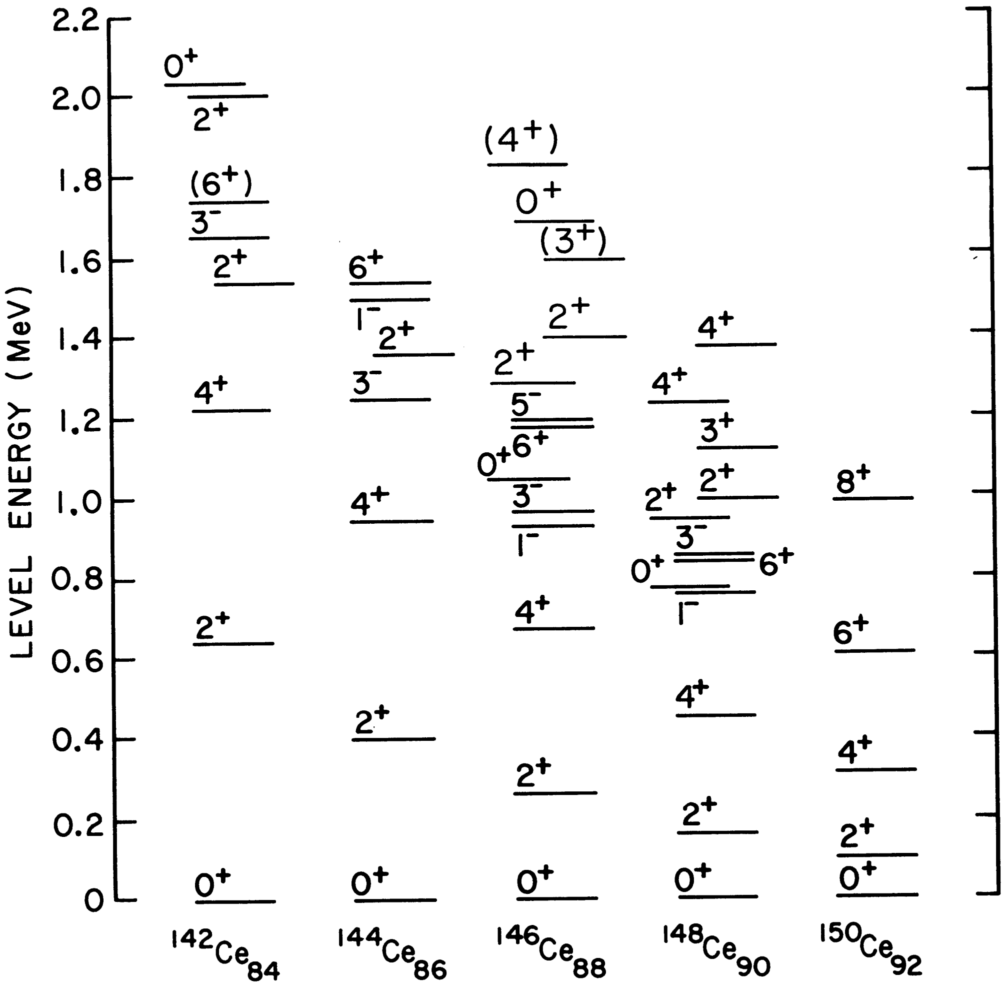

Fig. 3 Low-lying level systematics of the even Ce isotopes with N>82. Data were taken from the following references: ^{142}Ce,[8)] ^{144}Ce,[8,14)] ^{146}Ce (present study), ^{148}Ce,[13)] and ^{150}Ce.[8)]

these level assignments would lead to inconsistencies in the deexcitation patterns or to irregularities in the systematics. Smooth systematic trends are expected throughout this region, especially for the ground state and octupole bands, and to a lesser degree for the β and γ bands.

Based on the above arguments, the 2^+, 4^+, 6^+ ground state band[8)] and 3^- state at 961 keV[6)] reported in previous experiments are confirmed. The 5^- assignment for the 1183 keV level[9)] is chosen over the 3^- assignment from another previous work.[6)] The 2^+ and 1^- or 2^+ levels reported[6)] for 925 and 1043 keV levels are not confirmed. Our experimental results lead us to choose 1^- and 0^+ respectively, as the spins and parities for these levels.

The interpretation of the partial level scheme in terms of the (quasi-) band structure is shown in Fig. 1. The 0^+, 2^+, 4^+ and 6^+ members of the β band; 2^+ and 3^+ states in the γ band; and the 0^+ band head of the ββ band are shown.

Comparison of our proposed level structure with calculations using the Interacting Boson Approximation with neutrons and protons treated separately (IBA-2)[12,13)] is also shown in Fig. 1. In this case the boson Hamiltonian for positive parity states is represented by four parameters, the boson energy ε, the quadrupole-quadrupole neutron-proton interaction strength κ, and two parameters from the proton and neutron quadrupole operator terms χ_π and χ_ν. $\chi_\nu(\chi_\pi)$ is assumed to be independent of the number of neutrons (protons), as suggested by the microscopic theory.[14)] The IBA-2 calculations involved no parameter fitting. Parameters were generally extrapolated from the values determined for the heavier rare earth nuclides, Nd, Sm and Gd.[13)] χ_ν for ^{146}Ce was extrapolated from the heavier N=88 isotones. χ_π, on the other hand, was chosen using an interpolated value taken from Ba in addition to the $Z \geq 60$ isotopes. Thus the IBA is being tested here essentially as to its ability to predict the expected low lying level structure in ^{146}Ce. (A more detailed study of IBA-2 predictions for Ce isotopes with $142 \leq A \leq 150$ is given in another contribution to this meeting.[15)]) Despite the lack of parameter

Table 3

Reduced transition probabilities between levels in ^{146}Ce compared with IBA-2 calculations. One transition from each level is normalized to 100. IBA-2 parameters used in this calculation: $\chi_\pi = 1.2$, $\chi_\nu = -0.80$, $\kappa = 0.12$ $\varepsilon = 0.65$, effective charges for p and n = 1.

Transition	Transition Energy	Relative B(EZ) Experiment	IBA-2
$2_2^+ \rightarrow 0_1^+$	1274.4	100	100
$2_2^+ \rightarrow 4_1^+$	607.1	205	91
$2_2^+ \rightarrow 0_2^+$	231.2	18685	2721
$2_3^+ \rightarrow 0_1^+$	1382.1	100	100
$2_3^+ \rightarrow 4_1^+$	713.5	773	348
$2_3^+ \rightarrow 0_2^+$	338.8	2012	2551
$0_3^+ \rightarrow 2_1^+$	1398.9	100	100
$0_3^+ \rightarrow 2_2^+$	383.1	8439	37540
$0_3^+ \rightarrow 2_3^+$	275.5	31005	98400
$4_2^+ \rightarrow 2_1^+$	1550.3	100	100
$4_2^+ \rightarrow 2_2^+$	533.7	6103	76691
$4_2^+ \rightarrow 2_3^+$	(426.5)	<5201	14511

manipulation, the agreement between the theoretical and experimental level structures is very good. Table 3 gives the reduced transition probabilities, relative B(E2) values, for ^{146}Ce and their comparison with the values calculated using IBA-2. Only "pure" E2 transitions involving L=2 spin changes are compared since we have no in ormation on the amount of mixing present in our observed transitions. The results are relatively good with only one experimental value differing from its corresponding theoretical value by more than a factor of seven. These comparisons seem to indicate, at least in the case of ^{146}Ce and other Ce isotopes,[11,15] that the IBA works well in this crucial transitional region of the low-Z rare earths and that IBA-2 shows promise as a predictive tool in this region. A more extensive set of IBA-2 calculations is presently being investigated for nuclei in this light rare earth region which will allow us to elaborate further on these points in the near future.

Figure 2 shows the low lying level systematics of the known N=88 isotones and fig. 3 shows the analogous systematics

Table 4

Systematic trends of $E_{2_1^+}$ levels and the $E_{4_1^+}/_{2_1^+}$ ratios for even-even nuclei with $56 \leq Z \leq 64$ and $84 \leq N=92$. Data were taken from reference 8.

		Ba Z=56	Ce Z=58	Nd Z=60	Sm Z=62	Gd Z=64
$E_{2_1^+}$	N=84	602	641	696	747	784
	N=86	360	397	453	550	638
	N=88	199	258	301	334	344
	N=90	181	158	130	122	123
	N=92	142	98	76	82	89
$E_{4_1^+}/_{2_1^+}$	N=84	1.88	1.90	1.89	1.85	1.81
	N=86	2.32	2.36	2.30	2.15	2.02
	N=88	2.66	2.59	2.49	2.31	2.19
	N=90	2.83	2.87	2.93	3.00	3.02
	N=92	—	3.13	3.17	3.25	3.23

of the Z=58, (Ce) isotopes. Several interesting structural features centering around ^{146}Ce can be seen from these systematics. The 1^- and 3^- members of the octupole band cross (with the 1^- dropping below the 3^-) at ^{146}Ce for both the Z=58 isotopes and N=88 isotones. There is a noticeable drop of the 2_1^+ level energy and a corresponding increase in the $E_{4_1^+}/_{2_1^+}$ ratio (see Table 4) in going from Nd to Ce in the N=88 isotones. Note that this trend also exists in the Z=58 isotopes (Table 4) between N=86 and 88 (and to a lesser extent between N=88 and 90) but is much less severe than the trends observed between N=86 and 88 in Z=56 and N=88 and 90 in $Z \geq 60$. These features seem to indicate some tendencies towards attaining the prolate deformation present in the heavier rare earth nuclides at N=88 for the Ce isotopes. However, ^{146}Ce retains essentially a transitional character and this deformation does not clearly set in for Ce until N=90.[15] The Ce isotopes do not, however, show the abrupt onset of deformation characteristic of the Nd, Sm, Gd...($Z \geq 60$) isotopes between N=88 and 90 and to a lesser extent of Ba (Z=56) between N=86 and 88. The effect of fewer protons above the closed shell and the shift of deformation onset from N=90 to N=88 has "washed out" the sudden appearance of prolate deformation for the Z=58 isotopes.

4. Conclusions

The half life of ^{146}La was determined to be 6.0$\pm$ 0.4 s, in agreement with the reported value of 6.2s for the low spin ^{146}La isomer. The ^{146}Ce level scheme resulting from the decay of the low spin ^{146}La isomer has been considerably extended and refined. Four members of the ground state-band, three members each of the β and octupole bands, two states in the γ band, and the 0_3^+ band head of the $\beta\beta$ band have been identified. Comparisons of the experimental level energies and B(E2) values with IBA-2 calculations demonstrate the predictive power of this model. It is important, however, to extend our knowledge of unique spin-parity assignments and transition probabilities significantly in order to provide a more stringent test of IBA-2

Systematic evidence indicates that although some signs of the onset of deformation are present in ^{146}Ce, this deformation should not be considered to have occurred in Ce until N=90 (^{148}Ce). The onset of deformation is not sudden in Z=58 as it is for neighboring isotopic groups. Instead the transition to the well-deformed region follows the smooth pattern present throughout the Ce isotopes (N > 82).

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