OCTUPOLE CORRELATION EFFECTS NEAR $Z=56$, $N=88$

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Partial decay schemes for the very neutron-rich nuclei ^{146,148,150}Ce have been determined by the study of γ–γ coincidences in ^{252}Cf fission fragments. Similar behavior to that seen in ^{144,146}Ba, ^{148}Nd and ^{150}Sm, and interpreted in terms of strong octupole correlations, has been observed in yrast levels of ^{146}Ce but not in ^{148}Ce and ^{150}Ce. This is in agreement with the predictions of cranked mean field calculations.

The existence of a new island of nuclei which show characteristics of octupole deformation has recently been established experimentally with the discovery of interleaved negative and positive parity rotational bands in the nuclei ^{144,146}Ba [1]. Sequences of levels of alternating parity connected by strong electric dipole transitions have also been identified in the nuclei ^{146,148}Nd [2] and ^{148,150}Sm [3,4]. These bands are called octupole bands in the discussion below. They are very similar to those observed even more clearly in certain light actinide nuclei [5,6]. In some regions of the nuclear periodic table strong octupole correlations between the valence nucleons are indeed anticipated. They arise from the occurrence of closely spaced, opposite parity single-particle orbits with $\Delta l=3$ and $\Delta j=3$. These correlations may induce stable octupole deformation either in nuclear ground-states or in excited states when rotation increases. Specifically, cranked mean field calculations [7–9] predict this to happen at rather low spin in limited sets of accessible nuclei near $Z=56$, $N=88$ and $Z=88$, $N=132$. While these models have proven to be very successful in the second region (see refs. [5,6] and references therein), extensive tests of their predictive power for the first region have just begun. Isotopes of Xe, Ba, Ce, Nd and Sm with $N=84$, 86 and 88 plus ^{146}Ba are predicted [9] to be the best even–even candidates for the onset of a stable axially symmetric octupole deformation. This reflection asymmetric shape is expected to stabilize at spins $\geqslant 7\hbar$. Here, we present a severe test of the calculations for the Ce isotopes. In this case, the specific prediction [9] is that Ce isotopes with $N>88$ do not become octupole deformed, in contrast with the lighter isotopes. The data presented below provide strong support for the validity of the model; a single octupole band has been observed in ^{146}Ce$_{88}$ while the heavier ^{148,150}Ce isotopes do not exhibit the same characteristic yrast structure.

Fig. 1 shows part of the nuclear chart near $N=88$.

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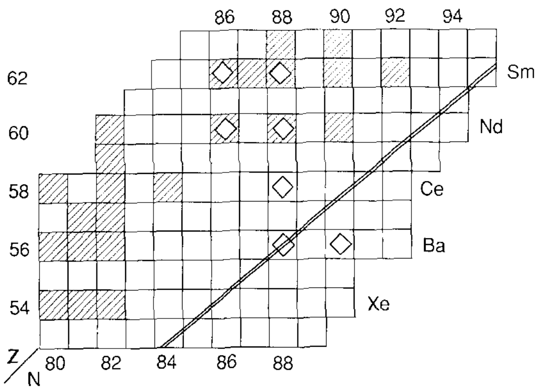

Fig. 1. Part of the nuclear period table showing nuclei where octupole-band-type structures have been found (diamonds). Stable isotopes are shown hatched. The double line shows, for each element, the most abundant isotope formed in the spontaneous fission of ^{252}Cf.

It includes the nuclei predicted to have an octupole shape. The nuclei which have already been observed to show features appropriate to rotation of asymmetric shapes are indicated as diamonds. It should be pointed out that a clear experimental signature of octupole deformation, i.e. an octupole band, will appear only for deformed nuclei with rotational bands. Thus, there is hope to find octupole deformation in nuclei with $N \geq 88$, which are known to be prolate deformed. Unfortunately, the nuclei with $N \leq 86$, such as $^{142}Ba_{86}$ [1] or $^{144}Ce_{86}$, lack rotational bands and signatures of octupole deformation are more difficult to interpret.

^{146,148}Ce and ^{150}Ce are very neutron-rich and can only be studied conveniently as final fragments in spontaneous fission. The average spin in these fragments is $\sim 7\hbar$ [10], and partial decay schemes of yrast or near-yrast levels with spins up to $\sim 12\hbar$ can be determined when the nucleus being observed is one of the strongly produced fragments. The measurements were performed on fission fragments from ^{252}Cf. ^{148}Ce is the most abundant Ce fragment (fig. 1) and comprises $\sim 2\%$ of the decay products of ^{252}Cf, compared with $\sim 3\%$ for the strongest product ^{144}Ba [11]. ^{146}Ce and ^{150}Ce form $\sim 1\%$ of the ^{252}Cf final fragments. The decay schemes were determined from prompt γ–γ coincidences observed with the Argonne-Notre Dame γ-ray facility which, at the time of the experiment, consisted of seven Compton-suppressed Ge detectors and one low energy photon spectrometer (LEPS). An additional coincidence was required in one of fourteen bismuth germanate detectors placed near the source and used as a multiplicity filter. The techniques and methods of analysis used have been described previously [1]. The starting points for disentangling the decay schemes were the $2_1^+ \to 0_1^+$ and $4_1^+ \to 2_1^+$ γ-rays known from earlier work [11] on ^{252}Cf decay products.

Fig. 2 shows samples of the coincidence spectra from which the decay schemes were constructed. Fig. 2a presents a sum of coincidence spectra obtained by gating on the $2_1^+ \to 0_1^+$, $4_1^+ \to 2_1^+$, $6_1^+ \to 4_1^+$ and $7^- \to 6_1^+$ transitions in ^{146}Ce. The spectrum of events in coincidence with the $6_1^+ \to 4_1^+$ transition in ^{148}Ce is given in fig. 2b. It can be seen that all the strong γ-rays have been assigned either to the Ce isotopes under investigation or to the complementary Zr fragments.

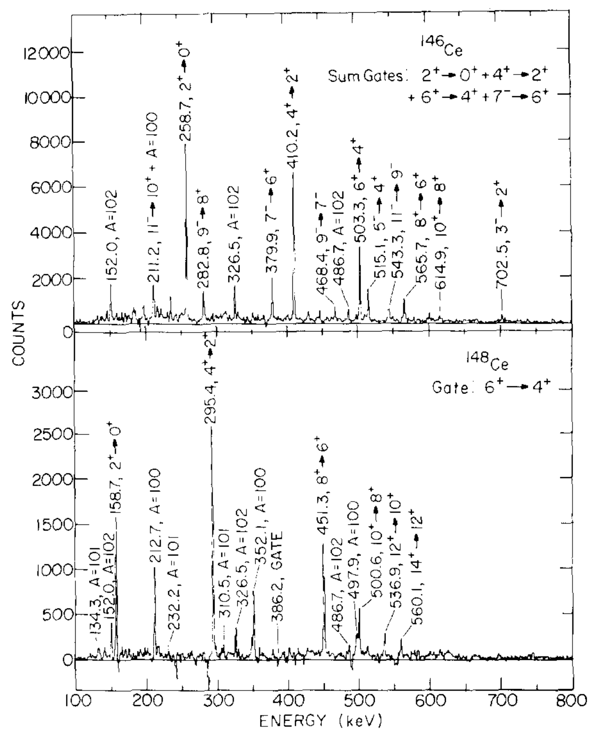

Fig. 2. Samples of coincidence spectra obtained in the present experiment. (a) shows a sum of spectra obtained by gating on the $2_1^+ \to 0_1^+$, $4_1^+ \to 2_1^+$, $6_1^+ \to 4_1^+$ and $7^- \to 6_1^+$ γ-rays in ^{146}Ce. (b) presents the spectrum in coincidence with the $6^+ \to 4^+$ transition in ^{148}Ce. All γ-rays which show up clearly are in ^{146}Ce and ^{148}Ce or in complementary Zr fragments. The assignments of the latter are referred to by mass number in the figure.

Fig. 3 shows the partial decay schemes obtained. The relative intensities, corrected for detector efficiencies, of γ-rays in coincidence with the $2_1^+ \to 0_1^+$ γ-ray are given in parenthesis, the $4_1^+ \to 2_1^+$ intensity being taken as reference. The 211.2 keV γ-ray in ^{146}Ce nearly overlaps the 212.5 keV $2_1^+ \to 0_1^+$ γ-ray in the complementary ^{100}Zr fragment, but was clearly resolved in the coincidence spectra seen in the LEPS detector, as was the 185.8 keV $8^+ \to 7^-$ γ-ray. ^{146}Ce shows patterns similar to those seen in e.g., ^{144}Ba [1] and ^{222}Th [6]. At spin $\geqslant 7\hbar$ two interweaved sets of levels occur, roughly approximating a single band, with the states interconnected by strong γ-ray transitions. The analogy with established schemes in ^{144}Ba, ^{148}Nd and ^{150}Sm strongly suggests assignments of the spins and parities to the levels according to their place in a single band appropriate for rotations of a reflection asymmetric nucleus (i.e. an octupole band). These assignments are supported, as in ^{144}Ba, by the observed strengths of the interconnecting γ-ray transitions compared to the relevant electric quadrupole decays. The strongly competing cross-overs suggest that they are of electric dipole character. Further support is given by previous likely assignments [12] of 5^- and 7^- to the levels at 1183 and 1552 keV, respectively. The interconnecting γ-rays are thus assumed to be electric dipole in nature and their intrinsic strengths may be calculated as in ref [1] from the relative intensities shown in fig. 3. In these calculations it was assumed that the band has constant intrinsic quadrupole moment which was derived from the measured [13] lifetime of 0.25(4) ns of the 2_1^+ level.

Table 1 shows the derived $B(\mathrm{E1})/B(\mathrm{E2})$ ratios for transitions from the different levels, and also the absolute $B(\mathrm{E1})$ values. The latter values are large and similar in size to those observed in other nuclei with octupole deformation. Within the rotational model, the electric dipole reduced transition probabilities $B(\mathrm{E1})$ may be related to an intrinsic dipole moment D_0. The value extracted from the weighted mean of the strengths given in table 1 for transitions from states with spin $\geqslant 8\hbar\sim$ is 0.20(1) e fm. Table 2 compares experimental values of D_0 found in octupole nuclei in the $Z\sim56$, $N\sim88$ region with predictions [9] based on the liquid drop model with shell corrections [14]. The overall agreement is very satisfactory.

^{148}Ce and ^{150}Ce show structures different from those seen in the $N=88$ nuclei. No side bands feeding into the ground state bands or interweaved with the ground state bands are seen in the decay schemes for levels with spins $<14\hbar$ (see fig. 2b). Essentially the

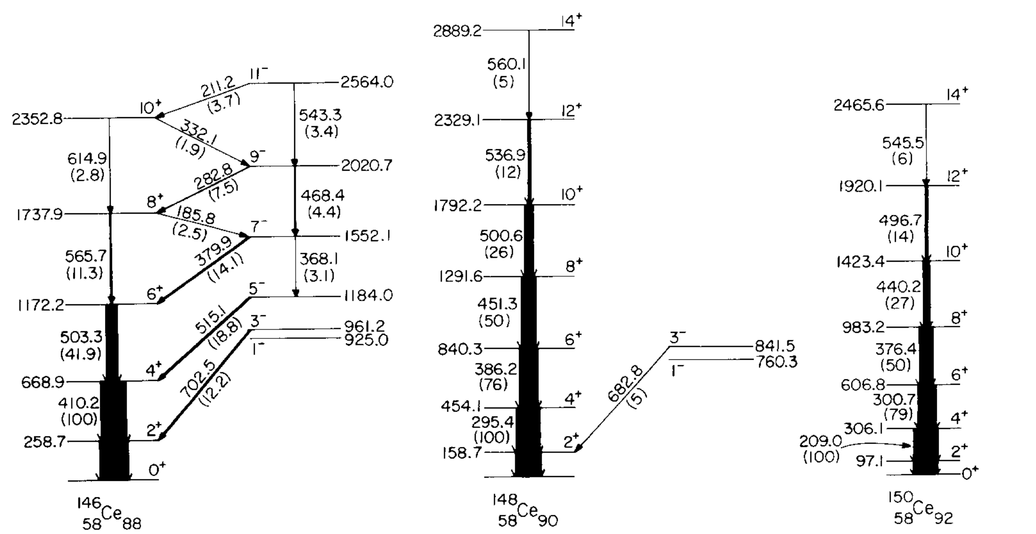

Fig. 3. Partial decay schemes for ^{146,148}Ce and ^{150}Ce. The errors on the level energies and γ-ray energies are $\leqslant 0.2$ keV; there is an additional uncertainty of 0.2 keV on the absolute γ-ray energies. The errors on the relative intensities vary from $\sim 30\%$ for the weak γ-rays to $\sim 5\%$ for the most intense. As discussed in the text, the spins and parities of the new levels established in this experiment are assigned by analogy with neighboring nuclei.

Table 1
Electric dipole transition strengths in ^{146}Ce.

E_γ (keV)	$I_i\pi_i \to I_f\pi_f$	I_γ	$B(E1)/B(E2)$ (10^{-6} fm^{-2})	$B(E1)/B(E1)^{w\,a)}$ ($\times 10^{-3}$)
368.1	$7^- \to 5^-$	3.1(8)	0.43(14)	
379.9	$7^- \to 6^+$	14.1(1.3)		0.86(28)
565.7	$8^+ \to 6^+$	11.3(1.1)	1.54(40)	
185.8	$8^+ \to 7^-$	2.5(6)		3.07(42)
468.4	$9^- \to 7^-$	4.4(6)	1.31(27)	
282.8	$9^- \to 8^+$	7.5(8)		2.60(54)
614.9	$10^+ \to 8^+$	2.8(6)	1.25(56)	
332.1	$10^+ \to 9^-$	1.9(7)		2.5(1.1)
543.2	$11^- \to 9^-$	3.4(6)	4.2(1.5)	
211.2	$11^- \to 10^+$	3.7(1.5)		8.3(3.8)

a) $B(E2; 2_1^+ \to 0_1^+)$ for ^{146}Ce$=0.21(2)\,e^2$b^2. A constant quadrupole moment was assumed although a change with spin is possible. $B(E1)^w$ for ^{146}Ce$=0.0174\,e^2\,b$.

Table 2
Experimental and predicted intrinsic dipole moments.

Nucleus	D_0 (exp) (e fm)	D_0 (theory) (e fm)
^{144}Ba	0.13	0.09
^{146}Ba	0.04	0.03
^{146}Ce	0.20	0.18
^{146}Nd	0.18	0.20
^{148}Nd	0.23	0.22
^{150}Sm	0.20	0.25

only levels observed in these experiments in both ^{148}Ce and ^{150}Ce form single quasi-bands taken to be $K^\pi=0^+$ reflection symmetric. Thus if octupole rotational-like structures occur in these isotopes they do not form part of the yrast sequences at spins $<14\hbar$.

There is a large difference in the observed feeding patterns of the yrast states in ^{148}Ce and ^{150}Ce compared to ^{146}Ce. If it is assumed that the net γ-ray intensity depopulating an observed level of spin J represents the entry point population of states of that spin, the average spin $\langle J\rangle$ in Ce fragments can be calculated in a straightforward way. $\langle J\rangle$ values for ^{146,148}Ce and ^{150}Ce are 5.5(4), 7.4(4) and 7.5(4), respectively. These differences may be partly due to unobserved near-yrast side bands in ^{146}Ce or to processes occurring at scission as recently suggested in ref. [15].

In summary, the present experiments show that the yrast levels between spins $\sim 7\hbar$ and $\sim 12\hbar$ in the $N=88$ isotones ^{144}Ba, ^{146}Ce, ^{148}Nd and ^{150}Sm all show the same behavior – a quasi-band such as would arise from rotation of a reflection-asymmetric nucleus. This is in agreement with predictions of cranked mean field calculations for these nuclei which suggests that the minimum potential energy surfaces at these spins have minima corresponding to octupole deformation. The nuclei ^{148}Ce and ^{150}Ce do not show octupole patterns in their yrast sequences; this is also in agreement with theory. The intrinsic dipole moments in the $N=88$ nuclei are reproduced rather well in calculations based on octupole deformation. All these observations illustrate the importance of strong octupole correlations in nuclei near $N=88$.

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