Crossings in alternating-parity bands of neutron-rich Ba nuclei

W. Urban¹, M.A. Jones¹, J.L. Durell¹, M. Leddy¹, W.R. Phillips¹, A.G. Smith¹,
B.J. Varley¹, I. Ahmad², L.R. Morss², M. Bentalab³, E. Lubkiewicz³ and N. Schulz³

¹Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, U.K.

²Argonne National Laboratory, Argonne, IL 60439, U.S.A.

³Centre de Recherches Nucléaires, IN2P3-CNRS/Université Louis Pasteur, 67037 Strasbourg, France

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Abstract

¹⁴⁴Ba and ¹⁴⁶Ba nuclei produced in the spontaneous fission of ²⁴⁸Cm have been studied using the EUROGAM II array. Spins and parities of excited levels have been deduced from triple- γ angular correlation and direction-polarization correlation measurements, which is the first use of these techniques in studies of fission product nuclei. Ground-state, alternating-parity bands have been extended significantly and crossing in these bands has been found in both isotopes. For the first time alternating-parity band termination by particle alignment has been observed.

Shortly after theoretical calculations predicted a region of octupole deformation around ¹⁴⁶Ba [1], the effect was found in even-even Ba nuclei produced in spontaneous fission [2]. Both theory and systematics of octupole-phonon energies suggested that the strongest effect should be found at the neutron number N=90. Experimental data showed however that octupole correlations are more pronounced at N=88 [2, 3]. Additional calculations [4] suggested that the electric dipole moment in ¹⁴⁶Ba is strongly reduced and although ¹⁴⁶Ba is octupole deformed it will not show strong E1 transitions. At that time it became evident that the Coriolis force can strongly affect octupole correlations in a nucleus. The correlations may be either suppressed due to particle alignment (band crossing) eventually causing termination of an alternating-parity band or enhanced due to the rearrangement of particles (enhancement of the octupole minimum in the nuclear potential). Both effects have been observed in the ground-state alternating-parity bands of ¹⁴⁸Sm and ¹⁵⁰Sm nuclei [5, 6, 7], though no band termination was seen. In the present work we report on similar phenomena found in neutron-rich barium nuclei. In the case of ¹⁴⁶Ba, particle alignment causes termination of an alternating-parity band, which is the first observation of such an effect.

The ¹⁴⁴Ba and ¹⁴⁶Ba nuclei studied were produced by the spontaneous fission of ²⁴⁸Cm. The fission source consisted of 5 mg of curium oxide embedded uniformly in a pellet of potassium chloride. Three and higher-fold γ coincidence data were collected using the EUROGAM II array at Strasbourg, which consisted of 52 large Ge detectors in anti-Compton shields including 24 four-crystal detectors - clovers, which also served as Compton polarimeters, and four LEPS detectors. Approximately $2.5 \cdot 10^9$ coincidence events were collected.

The data were sorted into three-dimensional spectra (cubes). Level schemes were constructed using triple- γ coincidences sorted into a $\gamma\gamma\gamma$ cube. The energy range on each axis of the cube was 3 MeV with a constant peak width energy calibration (FWHM of about 4 channels). The $\gamma\gamma\gamma$ cube contained about 2×10^{10} triple- γ events obtained by unfolding higher order coincidence events. Identification of new transitions in ^{144}Ba and ^{146}Ba was achieved by gating on known transitions [2].

Previously reported [2] ground-state and octupole bands have been extended to higher spins and new bands were found in both ^{144}Ba and ^{146}Ba . Level schemes of ^{144}Ba and ^{146}Ba nuclei obtained in the present work are shown in fig.1

Figure 1: Level schemes of ^{144}Ba and ^{146}Ba nuclei obtained in the present work.

Spins and parities of excited levels were found by analysing double and triple angular correlations and directional-polarization correlations of γ rays to find their multiplicities. Triple angular correlations, although more complex than double correlations, have much higher resolving power, which allows the study of complex γ spectra from spontaneous fission. To our best knowledge the triple angular correlation and directional-polarization correlation analysis presented in this work is done for the first time with gamma rays following spontaneous fission.

To study angular correlations in a triple- γ cascade with a randomly populated initial state, known as Directional Correlations from Oriented states (DCO) [8] a cube containing triple- γ coincidences between γ rays measured by Ge detectors at specific angles relative to each other was created (dco cube). Along the first axis of the cube were sorted energies of γ rays emitted in any direction. Along the second (third) axis were sorted energies of γ rays emitted at $\approx 90^\circ(180^\circ)$ with respect to the direction of the first γ ray. The dco cube provided two DCO values (or one DCO ratio, DCOR) for any triple cascade. In a simple case where the first transition γ_1 is unmixed and the multipolarities of two other transitions in a cascade are known, a measurement of one DCOR is sufficient to determine the multipolarity of γ_1 . DCOR values obtained from the dco cube for transitions in ^{144}Ba and ^{146}Ba are listed in Table 1 (the DCOR listed in Table 1 are associated with the first, unknown transition in a cascade, the two other transitions being stretched quadrupoles). More details of the method used here are given in ref.[9]. Comparing experimental values to predictions based on DCO theory provides information on the multipolarity of γ_1 . Predictions of DCOR for the EUROGAM II array give the following values [9]: for a stretched quadrupole transition DCOR=1.00, independent of the spin value of the initial level; for a stretched, unmixed dipole transition DCOR=1.20, independent of the spin value of the initial level; for a non-stretched, unmixed dipole transition DCOR=0.91 for a $4 \rightarrow 4 \rightarrow 2 \rightarrow 0$ cascade and for a stretched, unmixed dipole transition in a $3 \rightarrow 4 \rightarrow 2 \rightarrow 0$ cascade DCOR=1.28.

Table 1: DCO ratios and linear polarization values for transitions in ^{144}Ba and ^{146}Ba nuclei

^{144}Ba				^{146}Ba			
$E_\gamma(\text{keV})$	DCOR ^a	DCOR ^b	P_{exp}	$E_\gamma(\text{keV})$	DCOR ^a	DCOR ^b	P_{exp}
196.6	1.10(7)			307.5	1.16(5)	1.12(3)	0.06(3)
235.0	1.20(3)	1.08(3)	0.3(1)	332.7		0.92(1)	0.09(2)
271.4	1.24(6)			390.9	1.32(13)		
302.3	1.17(2)	1.15(2)	-0.02(4)	444.7	0.99(2)	0.93(1)	0.10(2)
330.8		0.93(1)	0.14(2)	510.9	1.16(7)		0.13(3)
388.0	1.28(9)		0.2(1)	524.2	1.01(3)	0.96(1)	0.04(2)
393.7	1.18(2)	1.12(1)	0.08(2)	544.4	0.95(12)		
431.5	1.02(1)	0.93(1)	0.09(2)	560.3	0.93(6)		0.15(8)
509.4	1.01(2)		0.09(3)	569.4	1.03(4)		0.15(5)
573.5	0.97(3)		0.07(4)	580.3	0.97(5)		0.14(5)
584.7	1.01(4)		0.13(5)	607.9	0.94(8)		-0.4(2)
623.0	1.05(7)			640.1		1.12(3)	0.07(6)
1029.8		0.86(5)	-0.1(3)	708.7	1.10(7)	1.11(2)	0.21(7)
1197.7		1.26(9)	-0.4(3)	916.3		0.92(4)	-0.9(4)
				986.3		1.16(4)	0.27(13)

^a from $\gamma\gamma\gamma$ angular correlation; ^b from $\gamma\gamma$ angular correlation

Where γ - γ coincidence data provided sufficient resolving power, γ - γ angular correlations

were analysed since γ - γ coincidences provide higher statistics, allowing the study of weak transitions. Two, two-dimensional spectra (matrices) were created. Along one axis of each matrix were sorted energies of γ rays emitted in any direction. Along the other axis were sorted energies of γ rays emitted at $\approx 90^\circ$ (first matrix) or at $\approx 180^\circ$ (second matrix) with respect to the direction of the first γ ray. The DCOR for a γ_1 transition in a γ_1 - γ_2 cascade was defined as the ratio of coincidence rates $N(\gamma_1, \gamma_2)$ obtained from the first and the second matrix, respectively, by gating on the same γ_2 line. DCOR values for transitions in ^{144}Ba and ^{146}Ba nuclei are listed in Table 1 (DCOR listed in Table 1 are associated with γ_1 of unknown multipolarity, γ_2 being a stretched quadrupole transition). These values should be compared against theoretical predictions for the EUROGAM II array: for a stretched quadrupole transition $\text{DCOR}=0.89$ independent of the spin value of the initial level; for a stretched, unmixed dipole transition $\text{DCOR}=1.09$ independent of the spin value of the initial level; for a non-stretched, unmixed dipole transition $\text{DCOR}=0.81$ for a $6 \rightarrow 6 \rightarrow 4$ cascade and $\text{DCOR}=0.82$ for a $8 \rightarrow 8 \rightarrow 6$ cascade and for a stretched, unmixed dipole transition in a $3 \rightarrow 4 \rightarrow 2$ cascade $\text{DCOR}=1.19$.

To find parities of levels, directional-polarization correlations were measured with the help of the clover detectors, acting as Compton polarimeters [10]. In the EUROGAM II array, the clover detectors were arranged in two parallel rings and the radiation source was placed between the centre of the two rings. For analysis, γ - γ coincidences were selected with one γ ray (γ_1) scattered inside a clover detector and the other (γ_2) observed in a conventional Ge detector at approximately 90° to the rings of clover detectors. Two γ - γ matrices (PER and PAR) were created out of these data. Along one axis of both matrices were sorted γ_2 energies. Along the other axis were sorted γ_1 energies resulting from the add-back of signals detected in a clover detector. These energies were accepted only when two elements of a clover detector fired, which indicated Compton scattering either in a direction perpendicular (event sorted into the PER matrix) or parallel (event sorted into the PAR matrix) to the direction of γ_2 . The linear polarization $P_{exp}(\gamma)$, of a γ transition with energy E_γ was measured using the formula:

$$P_{exp}(\gamma) = \frac{1}{Q(E_\gamma)} \times \frac{a(E_\gamma)N_\perp(\gamma) - N_\parallel(E_\gamma)}{a(E_\gamma)N_\perp(\gamma) + N_\parallel(\gamma)} \quad (1)$$

where $N_\perp(\gamma)$ and $N_\parallel(\gamma)$ are numbers of counts in the γ line of an energy E_γ , found in the gated spectra obtained from the PER and PAR matrices, respectively, by gating on the same, stretched quadrupole γ_2 transition. $Q(E_\gamma)$ is the sensitivity of the clover polarimeter taken from ref.[10] and $a(E_\gamma)$, called the geometrical calibration, is a correction factor for instrumental asymmetry. The geometrical calibration was determined by measuring a ratio $a(E_\gamma) = N_\parallel(E_\gamma)/N_\perp(E_\gamma)$ using unpolarized radiation. Two γ - γ matrices were sorted, where γ_1 was an add-back signal and γ_2 was observed by *any* of EUROGAM detectors. The isotropic distribution of γ_2 ensured that γ_1 detected by the clovers was unpolarized. The geometrical calibration found in this work was $a(E_\gamma)=0.980(5)$, independent of E_γ .

Linear polarization values for γ transitions in ^{144}Ba and ^{146}Ba nuclei obtained in this work are listed in Table 1. They can be tested against theoretical values for directional-polarization correlations P_{th} calculated for the EUROGAM II array (upper[lower] sign applies for electric[magnetic] transition): for a stretched quadrupole transition $P_{th}=\pm 0.14$ independent of spin value of the initial level; for a stretched unmixed dipole transition

$P_{th} = \pm 0.09$ independent of the spin value of the initial level and for a $\Delta I = 0$, unmixed dipole transition $P_{th} = \mp 0.25$ in a $6 \rightarrow 6 \rightarrow 4$ and $P_{th} = \mp 0.23$ in a $8 \rightarrow 8 \rightarrow 6$ cascade.

DCO ratios and linear polarization values listed in Table 1 allow unique spin and parity assignment to many levels in ^{144}Ba and ^{146}Ba . In particular we confirmed negative parity for the 1355.3 keV level (hence for the band on top of the 1038.8 keV level) in ^{144}Ba suggested previously from the intensity of barium K_α X-rays associated with the 115.5 keV transition [2]. In ^{144}Ba our data indicate spin and parity $I^\pi = 6^{(-)}$ for the 1991.5 keV level and $I^\pi = 7^{(+)}$ for the 2159.3 keV level. In ^{146}Ba we could assign negative parity to the band on top of the 821.2 keV level. Negative parity for this band has been proposed previously based on systematics for the 3^- octupole excitation in this region [2]. DCO ratios and linear polarization values for the 607.9, 708.7, 916.3 and 986.3 keV transitions allow unique spin and parity assignment for the side bands of ^{146}Ba .

The difference between excitation schemes of ^{144}Ba and ^{146}Ba noticed previously [2], is now even more apparent. ^{144}Ba displays features characteristic of strong octupole correlations. A regular, alternating-parity band, extended now up to spin $I = 17$, shows strong interleaving E1 transitions. $B(E1)/B(E2)$ branching ratios for this band are shown in fig. 2. They are of the order of 10^{-6}fm^{-2} and stay constant up to the highest observed spin, suggesting that the alternating-parity band possibly continues to still higher spins.

Figure 2: $B(E1)/B(E2)$ branching ratios in the ground-state alternating-parity band of ^{144}Ba (circle) and ^{146}Ba (diamonds). Bar at spin $I = 5$ shows lower limit for $B(E1)/B(E2)$ branching ratio for the 1038.8 keV level in ^{144}Ba . Filled diamonds represent $B(E1)/B(E2)$ branching ratios for the 2191.4 keV and 2516.2 keV levels in ^{146}Ba .

Five non-yrast levels were observed, which form two side-bands with band-heads at 1991.5 keV and 2159.3 keV, respectively. It is likely that these two unnatural parity side bands form an alternating-parity band with simplex $s = -1$, as observed in ^{148}Sm [7]. In the case of ^{144}Ba , nuclear rotation seems to enhance octupole correlations and the presence of the $s = -1$ band suggests that octupole deformation develops at medium spins.

The octupole interaction in ^{144}Ba is strong enough to prevent sudden particle alignment, observed in reflection symmetric nuclei. This is illustrated in fig.3, where an alignment plot is drawn for the ground-state band and the negative parity band (filled and open circles, respectively). Both bands gain alignment gradually and there is no indication of band crossing.

Figure 3: Alignments in ground-state alternating-parity bands of ^{144}Ba and ^{146}Ba . Harris parameters used were $\Theta_0=19\hbar^2/\text{MeV}$ and $\Theta_1=80\hbar^4/\text{MeV}^2$.

^{146}Ba , with only two neutrons more, displays quite different features. $B(E1)/B(E2)$ branching ratios are two orders of magnitude lower than in ^{144}Ba and E1 transitions between the ground-state band and the octupole band are not seen above spin $I=9$. A new distinctive feature found in ^{146}Ba are two, negative-parity side-bands. Properties of these bands suggest their two-quasiparticle character. The band on top of the 1944.9 keV level crosses the octupole band. This band decays also to the ground-state band and $B(E1)/B(E2)$ branching ratios are of the same order as for the octupole band, as shown in fig.2 (filled diamonds), but above spin $I=11$ E1 transitions are not seen. It is interesting to look at the alignment plots of the ground-state band and the negative-parity band in ^{146}Ba , shown in fig.3 as filled and open diamonds, respectively. Unlike ^{144}Ba there is a pronounced crossing in the ground-state band of ^{146}Ba at $\hbar\omega \approx 0.28$ MeV. A large gain in alignment, of more than 8 spin units suggests the alignment of a high-spin orbital, possibly a pair of $i_{13/2}$ neutrons. Up to spin $I=13$ the negative parity band on top of the 821 keV level shows similar alignment gain as the analogous band in ^{144}Ba . However if one follows the yrast line for odd-spin, negative-parity levels, an alignment is observed at $\hbar\omega \approx 0.29$ MeV, which corresponds to crossing of the negative parity band by the band on top of the 1944.9 keV level.

To explain the apparent difference between $B(E1)/B(E2)$ branching ratios in ^{144}Ba and ^{146}Ba it has been proposed [4] that due to shell effects the electric dipole moment in ^{146}Ba is strongly reduced, although the nucleus still has octupole deformation. Up to spin

$I=11$ data shown in fig.2 are consistent with this picture. However at higher spins both the ground-state and the negative parity band display crossing characteristic of particle alignment in a reflection symmetric nucleus. This suggests that above spin $I=11$ there is no octupole deformation in ^{146}Ba . This observation is an explicit confirmation of a long standing prediction [4] of termination of an alternating-parity band by particle alignment.

In summary, we have studied the neutron-rich nuclei ^{144}Ba and ^{146}Ba , populated in the spontaneous fission of ^{248}Cm . New bands were found, which cross with ground-state alternating-parity bands. Spins and parities of levels have been determined from double and triple angular correlations and directional-polarization correlations of γ rays. Strong octupole correlations have been observed in ^{144}Ba , where the simplex $s=+1$ band has been observed up to spin $I=17$. New bands in ^{144}Ba form a simplex $s=-1$ band, which suggests the presence of octupole deformation in ^{144}Ba at medium spins. In ^{146}Ba , the octupole effects are weaker and disappear at medium spins, where both the ground-state band and the octupole band undergo band crossings, after which ^{146}Ba becomes reflection symmetric.

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