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STABLE AND VIBRATIONAL OCTUPOLE MODES IN Mo, Xe, Ba, La, Ce AND Nd

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Evidence is presented for stable octupole deformation in neutron-rich nuclei bounded by Z = 54-58 and N = 85-92. To either side of this region negative parity bands built on more vibrational type octupole modes are observed in ^{140}Ba and ^{152,154}Nd. The largest stable octupole deformation (β_3 - 0.1) is found in ^{144}Ba$_{88}$. The theoretically predicted quenching (β_3 - 0) of stable octupole deformation at higher spins is found in ^{146}Ba. There is good agreement between theory and experiment for the strongly varying electric dipole moments as a function of mass for $^{142-146}$ Ba. In odd-A ^{143}Ba and odd-Z ^{145}La we observe parity doublets, two pairs of positive and negative parity bands with opposite spins. In ^{146}La a strong coupled ground band with symmetric shape coexists with the asymmetric octupole shape which stabilizes above about spin 19/2^{+}. In ^{145,147}La a strong reduction in E2 strength around 25/2 from band crossing is observed. The isotope ^{109}Mo was identified and a new region of stable octupole deformation is identified in ^{107,109}Mo centered around N = 64-66 as earlier predicted. This is the first case of stable octupole deformation involving only one pair of orbitals.

1 Introduction

Studies of the spontaneous fission (SF) of heavy elements like ^{252}Cf, and ^{248}Cm, with large detector arrays like Gammasphere and Eurogam are providing a wealth of new insight into the changing structures of neutron-rich nuclei [1]. One important discovery was that of stable octupole deformation centered around Z = 56,58, N = 88 in ^{144,146}Ba [ref. 2] and ^{146}Ce [ref. 3] associated with the $\nu f_{7/2}$-$\nu i_{13/2}$ and the $\pi d_{5/2}$-$\pi h_{11/2}$ orbits. With much larger detector arrays, that evidence has been extended to higher spins and to $^{140-148}$Ba and likewise found in odd-A ^{143}Ba [refs. 1,4,5,6] and ^{145,147}La [refs. 7,8]. These new data [1,4] also provided the first evidence for the theoretical prediction [9] of the vanishing of stable octupole deformation at higher spin.

Static octupole deformation may be induced in nuclei where the Fermi level lies between single particle orbitals of the type $|N,L,j\rangle$ and $|N + 1, L + 3, j + 3\rangle$ (e.g., $p_{3/2}$-$g_{9/2}$, $d_{5/2}$-$h_{11/2}$, $f_{7/2}$-$i_{13/2}$, etc.), because such orbitals couple

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strongly through the octupole potential term Y_{30} [10,11]. Calculations indicate that stable octupole effects (enhanced E1 transitions between bands) may be observed in nuclei with Z and N around (34), 56, 88, 134. It was thought that octupole coupling for both protons and neutrons in a nucleus was needed to give sufficient enhancement to produce observable stable octupole effects. This is the case in the Ba-Ce and Rn regions. The occurrence of stable octupole deformation in N = 64-66 nuclei also has been predicted by Cottle [12]. Recently, evidence for stable octupole deformation was found in $^{107}Mo_{65}$ and the newly discovered $^{109}Mo_{67}$ [ref. 13] based only on one nucleon pair of orbitals for the first time. More vibrational-like octupole structures are observed in ^{140}Ba (6,14,15) and $^{152,154}Nd$ [16].

2 Stable Octupole Deformation in $^{140\text{-}148}Ba$ Nuclei

With Gammasphere (1993 ^{252}Cf SF data) new high spin states were observed in $^{142\text{-}146}Ba$, and the first evidence for octupole deformation in an odd-A nucleus was reported in N = 87, ^{143}Ba [ref. 1,4]. Figure 1 gives our extended $^{140\text{-}148}Ba$ level schemes extracted from our 1995 Gammasphere data [5,6,15]. These level schemes are very similar to those simultaneously extracted from Eurogam II in SF of ^{248}Cm [refs. 14, 17]. The only significant difference in level assignments is in the 641-722 keV cascade into the 3153.2 keV 11^- level in ^{142}Ba where we assign this cascade to the negative parity band [5] and Urban et al. [14] assign the 641.0 as an E1 crossing transition with the 722 placed in the yrast cascade with only a dashed yrast transition to connect the 3794.0 keV level to the 10^+ level. Important contributions of Urban et al. [14] and Jones et al. [17] were the establishment of the spins and parities of the levels assigned earlier on systematics in the even- and odd-A Ba isotopes from directional correlation and polarization measurements.

A striking feature seen in Fig. 1 is the intertwined E1 transitions between the positive and negative parity bands to quite high spin in ^{144}Ba but not continuing in ^{146}Ba. These E1 transitions are strongly enhanced in $^{142,144}Ba$ B(E1) ~ 1×10^{-3} w.u. to give evidence for stable octupole deformation but are reduced by a factor of 10-100 in ^{146}Ba. This drop in E1 strength in ^{146}Ba was first noted by Phillips et al. [2]. In Fig. 2 the intrinsic electric dipole moments, D_0, extracted from the B(E1) values are given averaged for high $I > 8\hbar$ and low spin state $I < 7\hbar$ data. D_0 are reported in refs. [1,4] and here for $^{142,144,146}Ba$, and in ref. [14] and here for ^{145}Ba. In $^{142,144}Ba$, D_0 is significantly larger for the higher spin data to show an enhancement of the

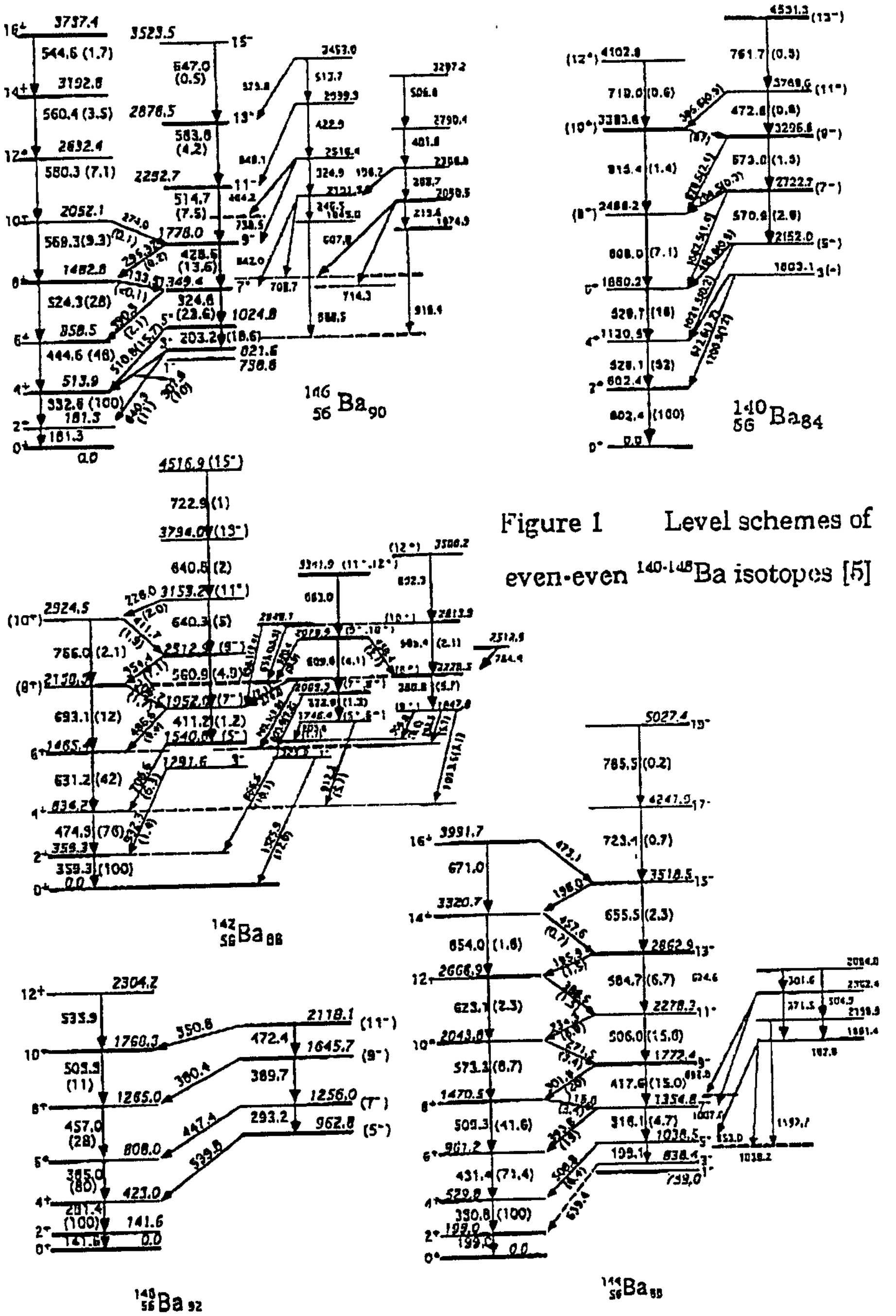


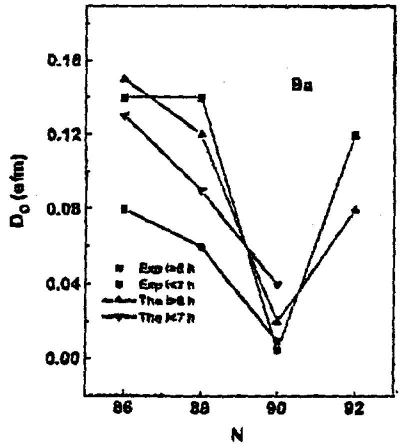
Figure 1 Level schemes of even-even $^{140\text{-}148}$Ba isotopes [5]

stable octupole deformation with rotation, while for ^{146}Ba the reverse occurs with a sharp decrease and then undetectable E1 transition strength above spin 10^+ to indicate a vanishing of β_3 at higher spins [1,4,5]. The ^{148}Ba D_0 for high spins is similar to those of ^{142,144}Ba to indicate the stable octupole deformation is again stabilized there.

The D_0 calculations of Butler and Nazarewicz [18] in the shell correction method based on the reflection asymmetric Woods-Saxon model nicely reproduce the data (Fig. 2) while the Interacting Boson Model cannot [19]. The D_0 in ^{146}Ba is dramatically reduced because of the very small shell correction term (cancellation between proton and neutron contribution to D_0^{shell}) and the negligible macroscopic contribution D_0^{mac} (cancellation between the reorientation term and the neutron-skin term).

In the moments of inertia for $^{142\text{-}148}$Ba (Fig. 3), one sees in ^{146}Ba a sudden sharp increase (backbend) above 10^+ that is not seen in ^{142,144,148}Ba where only smooth upbends are seen. Cranked shell model calculations for the Ba-Ce nuclei indicate that around $N = 88$ at intermediate spins the stable octupole deformation increases and the octupole minima are much better separated (see Fig. 4) [9]. However, at higher spin and rotational frequency the octupole deformation is predicted to disappear as seen in Fig. 4. A shape transition towards $\beta_3 = 0$ is expected in ^{146}Ba at frequencies above 0.3 MeV after the alignment of $\nu i_{13/2}$ and $\pi h_{11/2}$ pairs [9]. The new data for ^{146}Ba show the ground band is crossed above 10^+ (Fig. 3), and no intertwined connecting transitions are seen above 10^+. These data [1,4,5] provided the first evidence for the theoretical prediction of the vanishing of β_3 above $\hbar\omega = 0.3$ MeV [9]. However, in ^{144}Ba, where there is no backbend in J_1, the new data to 16^+ indicate no reduction in the E1 strength for these higher spins compared to the lower spin states. Indeed, the average D_0 values are larger for the higher spin states than for the lower spin states (Fig. 2), to indicate rotation enhances the stable octupole deformation in ^{144}Ba in agreement with theory.

In odd-A nuclei with stable octupole deformation reflection asymmetry occurs, and the level patterns are similar to rotational bands in reflection-asymmetric molecules including two pairs of parity doublets with the same spins but opposite parities in each doublet, the simplex $s = i$ and $-i$ doublets with each intertwined by enhanced E1 transitions [20]. The first two E1 intertwined opposite parity bands were observed in ^{145}Ba (1,4) (Fig. 5) and



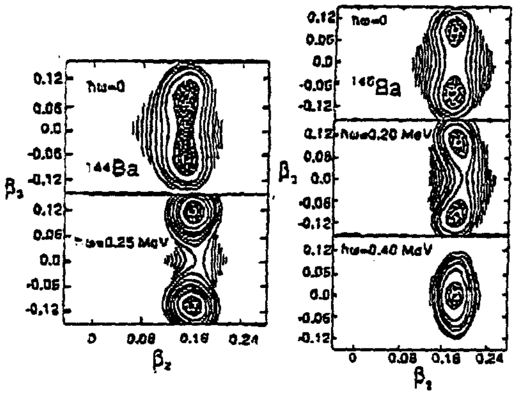


Figure 2. Experimental and calculated intrinsic dipole moments.

Figure 4. The influence of β_3 on the total Routhian surface in the (β_2,β_3) plane for ^{144}Ba at hω=0, 0.2, and 0.4 MeV [9]

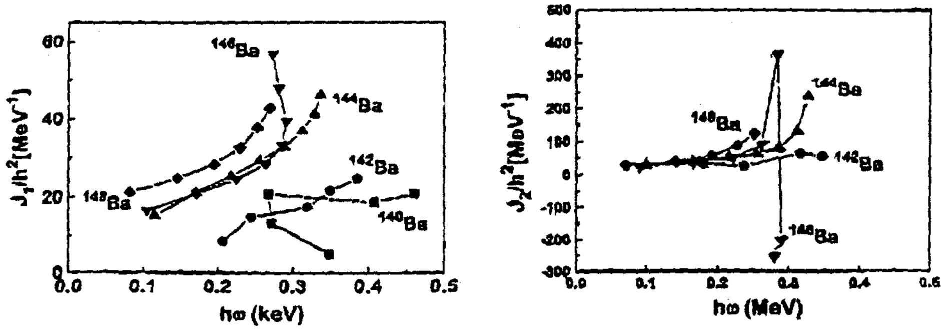
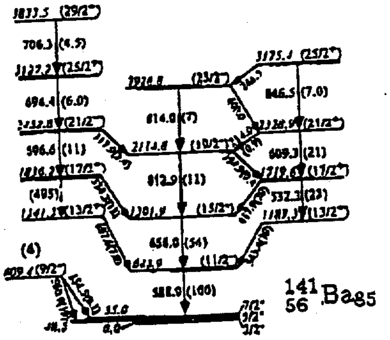
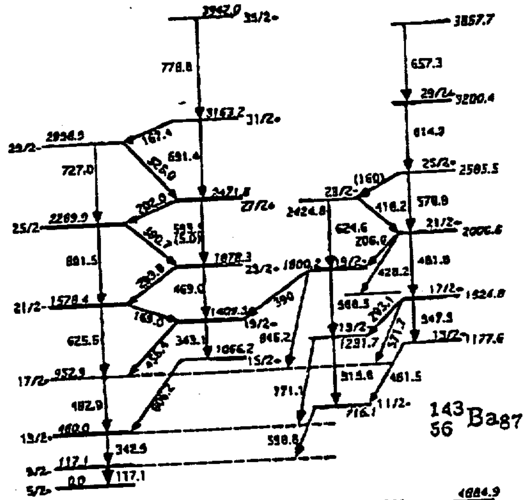


Figure 3. Yrast band moments of inertia (J_1 and J_2) as a function of rotational frequency (hω) for even-even Ba nuclei.

Figure 5. Levels of odd-A ^{141,143,145}Ba isotopes [4,5]





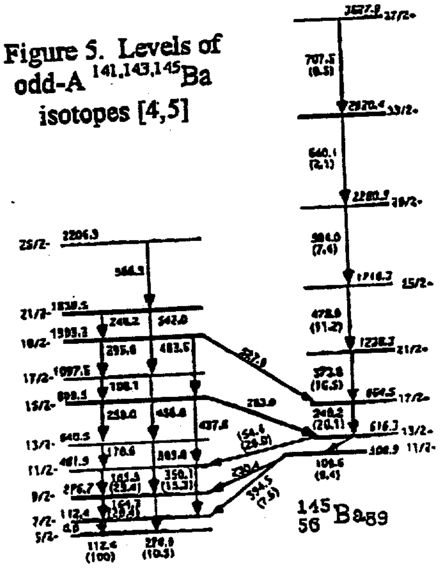


Figure 6. Levels of ^{144,146,148}Ce isotopes [1,2,4]