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Octupole correlations in the odd-Z nuclei $^{148-151}$Eu

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The effects of octupole correlations in the Z=63 nuclei $^{148-151}$Eu are studied. The persistency of octupole instability through the transitional region of near-spherical ($N \leq 85$) towards prolate nuclei ($N \geq 88$) is established and discussed. Intrinsic dipole moments, which are experimentally inferred from the measured electric dipole transition rates observed between parity doublets, are used to characterize the strength of the octupole correlations.

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Shortly after finding octupole deformation in actinides (see [1] and references therein), it was suggested that the effect could also be found in neutron rich lanthanides [2]. Nuclei in this region are predicted to exhibit enhanced octupole correlations because the Fermi levels for $Z \simeq 64$ and $N \simeq 82$ lie in between the ($\pi d_{5/2}, \pi h_{11/2}$) and the ($\nu f_{7/2}, \nu i_{13/2}$) orbitals in the proton and neutron sides, respectively. Such pairs of orbitals couple via the Y_{30} operator to a 3^- state inducing in the mean field an instability towards β_3 deformations. In particular, for nuclei in the neighborhood of the doubly closed shell nucleus (no more than 4–6 valence particles/holes outside the closed shell) the 3^- phonon state is a recognizable feature of the low-lying excitations [3], since it couples to most of the single- and multi-particle-hole (multi-p-h) configurations. Further addition of valence particles tends to induce a sufficiently large quadrupole deformation in the nuclear mean field, making collective rotational structures the dominating excitation mechanism. It is the region of weakly deformed nuclei that one hopes is sensitive to the smaller effects produced by reflection asymmetric mean fields. Furthermore, experimental work [4] on odd-Z nuclei in this region seems to suggest that octupole correlations are enhanced by the odd-proton. Quadrupole deformation increases drastically with neutron number in the $82 < N < 88$ region and above $N = 90$ quadrupole effects dominate the nuclear decay scheme. Therefore the isotopes $^{148}_{63}\mathrm{Eu}_{85}$ to $^{151}_{63}\mathrm{Eu}_{88}$ were chosen as a set of good candidates where the β_2 deformation is still not the main dominating feature of the mean field. Details of these studies are published elsewhere [5–8] and in this report we focus on the specific subject of octupole excitations in these nuclei. The coupling of the 3^- phonon to particular multi-p-h states as identified in ^{148}Eu, ^{149}Eu, and other $N = 85$ and $N = 86$ isotones is discussed. In the more rotational-like structures identified in ^{150}Eu and ^{151}Eu, enhanced $B(E1)$ moments, characteristic of rotational nuclear shapes with either a dynamic or static octupole deformation, are evaluated. In this mass region calculations show [2] that octupole instability is induced by rotation.

The available high-j single-particle states in the discussed region are the $\pi d_{\frac{5}{2}}, \pi g_{\frac{7}{2}}$, and $\pi h_{\frac{11}{2}}$ proton orbitals and the $\nu f_{\frac{7}{2}}, \nu h_{\frac{9}{2}}$, and $\nu i_{\frac{13}{2}}$ neutron orbitals. The ground state configurations of the europium nuclei (with $Z = 63$) have a proton hole in the $\pi d_{\frac{5}{2}}$ proton orbital, while the neutrons are occupying the $\nu f_{\frac{7}{2}}$ orbital. A common feature of Eu nuclei is the existence of a low-lying isomeric state. This state is due to the promotion of the odd proton into the $\pi h_{\frac{11}{2}}$ orbital. Any of the available valence neutrons can be promoted into either the $\nu h_{\frac{9}{2}}$ of $\nu i_{\frac{13}{2}}$ orbitals, forming high-spin multi-p-h states. A detailed discussion of all the high-spin multi-p-h states observed in ^{148}Eu and ^{149}Eu are given in Refs. [5–7]. Here we will concentrate only on the states originating from the coupling of the octupole phonon to the structures built on top of the isomeric level. These are shown in Figs. 1 and 2 for $N = 85$ and $N = 86$ isotones, respectively.

In the odd-Z isotones we observe a splitting in the phonon multiplet (see Figs. 1 and 2). This splitting is due to the interaction between the odd proton occupying the $\pi h_{\frac{11}{2}}$ orbital and the larger $\pi h_{\frac{11}{2}} \pi d_{\frac{5}{2}}^{-1}$ component in the octupole phonon wave function, $|\langle hd|H|3^-\rangle|$. For members of the multiplet resulting from the angular momentum coupling of a 3^- state to an $\frac{11}{2}$ state, the energy shifts introduced are given by [3]

$$\delta E = (2 \cdot 3 + 1) \begin{pmatrix} 3 & \frac{11}{2} & \frac{5}{2} \\ \frac{11}{2} & 3 & I \end{pmatrix} \frac{|\langle hd|H|3^-\rangle|^2}{\Delta}, \qquad (1)$$

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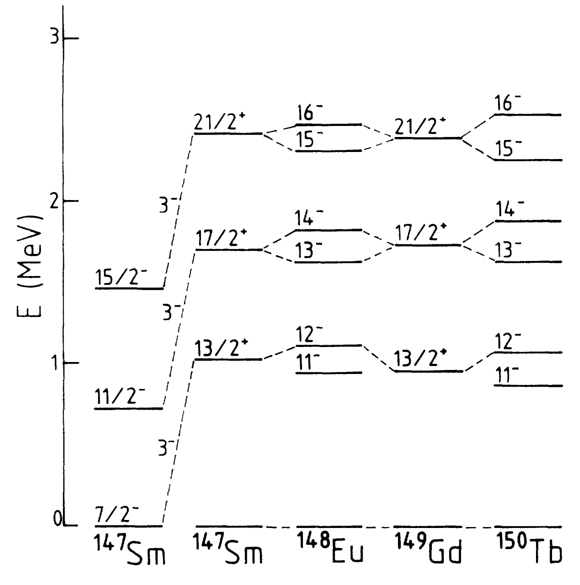

FIG. 1. Comparison of the $\nu(f_{\frac{7}{2}})^3 \otimes 3^-$ states in the $N = 85$ isotones. Data for ^{147}Sm, ^{149}Gd, and ^{150}Tb are taken from Refs. [12], [13], and [14], respectively.

where $\Delta = E(\pi h_{\frac{11}{2}}) - E(\pi d_{\frac{5}{2}}^{-1}) - \hbar\omega_3$. The single-particle energies for the $\pi h_{\frac{11}{2}}$ and $\pi d_{\frac{5}{2}}^{-1}$ are obtained from experimentally measured states in ^{149}Eu [6], resulting in $E(\pi h_{\frac{11}{2}}) - E(\pi d_{\frac{5}{2}}^{-1}) = 2.6$ MeV. The 3^- phonon energy $\hbar\omega_3 = 1.6$ MeV, representing an average of the experimentally extracted phonon energies in this mass region. The matrix element $|\langle hd|H|3^-\rangle|$ can then be extracted from the experimentally measured energy difference between the 11^- and 12^-, 13^- and 14^-, 15^- and 16^- states. The $|\langle hd|H|3^-\rangle|$ interaction energy obtained for the $N = 85$ isotones ^{148}Eu and ^{150}Tb, as well as the $N = 86$ nuclei ^{149}Eu and ^{151}Tb, are shown in Table I. The latter were extracted using the energy differences between the $\frac{15}{2}^+$ and $\frac{17}{2}^+$, $\frac{19}{2}^+$ and $\frac{21}{2}^+$, $\frac{23}{2}^+$ and $\frac{25}{2}^+$ states in ^{149}Eu and ^{151}Tb (see Fig. 2). From Table I we see on average a larger $|\langle hd|H|3^-\rangle|$ interaction for the $N = 86$, ^{149}Eu and ^{151}Tb nuclei as compared to the $N = 85$, ^{148}Eu and ^{150}Tb nuclei.

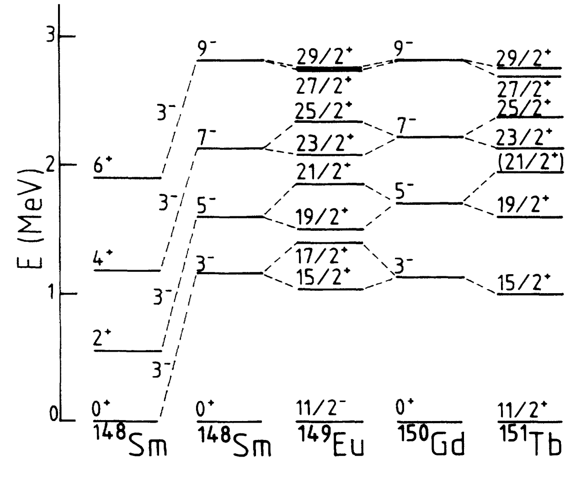

FIG. 2. Comparison of the $\nu(f_{\frac{7}{2}})^4 \otimes 3^-$ states in the $N = 86$ isotones. Data for ^{148}Sm, ^{150}Gd, and ^{151}Tb are taken from Refs. [11], [15], and [16], respectively.

From the measured $B(E1)/B(E2)$ branching ratios in the different nuclei investigated one can extract $B(E1)$ transition rates. Enhanced $B(E1)$ rates are a good signature for a reflection asymmetric nuclear shape, since they represent a large intrinsic dipole moment D_0. The intrinsic dipole moment D_0 can be obtained for a rotating nucleus via the formula [9]

$$B(E1; I_i \to I_f) = \frac{3}{4\pi} D_0^2 \langle I_i K_i 10 | I_f K_f \rangle^2. \qquad (2)$$

Although the europium nuclei investigated are not good rotors, formula (2) provides a systematic way to extract D_0 which can be compared with other experimental intrinsic dipole moments obtained for neighboring nuclei.

Values of $B(E1)$ are extracted from the observed $B(E1)/B(E2)$ branching ratios as given in Table II using $B(E2)$ rates calculated with the rotational model formula

$$B(E2; I_i \to I_f) = \frac{5}{16\pi} Q_0^2 \langle I_i K_i 20 | I_f K_f \rangle^2. \qquad (3)$$

The quadrupole moment Q_0 is assumed to be constant for all spins and is estimated from an interpolation of measured quadrupole moments in the even-even nuclei. The errors associated with the $B(E1)$ values tabulated (Table II) are only reflecting the experimental error in the measured branching ratios. The systematic error introduced by the assumption of a constant Q_0 in calculating the $B(E2)$ values is not taken into consideration. The D_0 values obtained using formula (2) are also given in Table II, and shown in Fig. 3 as a function of spin above the initial "bandhead" state (I_{bandhead}). Figure 3 shows a tendency of D_0 to increase with spin, which is clearly observed in ^{151}Eu. This indicates an increase in octupole correlations with increasing spin, consistent with Woods-Saxon-Bogolybov calculations [2], made for nuclei in this mass region.

To see the dependence of the octupole correlations on neutron and proton number, we compare our measured values with the systematics of Ref. [10], compiled in Fig. 4. As predicted by theory, strong $B(E1)$ rates are observed in the Lanthanide region $56 < Z < 64$ and $82 < N < 92$. The $B(E1)$ rates seem to be larger for even-even nuclei. A reduction in $B(E1)$ rates for the odd-N nuclei by a factor of 10–100 is systematically observed. This reduction is mostly a single-particle effect. When either a fully aligned $\nu f_{\frac{7}{2}}$ or $\nu i_{\frac{13}{2}}$ orbital is occupied, the Y_{30} operator has a decreased matrix element, implying less instability towards octupole deformations.

For isotones with an even neutron number the odd-Z nuclei have also reduced $B(E1)$ values, although this effect seems to be less pronounced than for the isotope chains where the odd-N blocking reduces the $B(E1)$ rates drastically.

The staggering due to the Pauli blocking on the pro-

TABLE I. The $\langle hd|H|3^-\rangle$ interaction energies estimated from the level splitting in the $N = 85$ and $N = 86$ isotones.

$j^- \to (j-1)^-$	^{148}Eu (MeV)	^{150}Tb (MeV)	$j^- \to (j-1)^-$	^{149}Eu (MeV)	^{151}Tb (MeV)
$12^- \to 11^-$	0.55	0.66	$17/2^+ \to 15/2^+$	0.77	0.79
$14^- \to 13^-$	0.58	0.73	$21/2^+ \to 19/2^+$	0.74	0.76
$16^- \to 15^-$	0.52	0.71	$25/2^+ \to 23/2^+$	0.65	0.64

ton side is not as large as on the neutron side, because both the $\pi d_{\frac{5}{2}}$ and the $\pi h_{\frac{11}{2}}$ proton orbitals are occupied. However, the neutron Fermi level lies well below the lowest $\nu i_{\frac{13}{2}}$ neutron orbital at $N = 86$. A larger staggering of $B(E1)$ rates as function of neutron number is expected, since occupying the $\nu i_{\frac{13}{2}}$ neutron orbital in the odd-neutron nuclei results in a larger effective Pauli blocking, compared to the even-N nuclei. At larger neutron numbers ($N \simeq 92$), when the $\nu i_{\frac{13}{2}}$ orbital comes also close to the Fermi level, there is some evidence that the odd-even effect for the neutrons also decreases. A particular striking effect is the combination of blocking the neutrons and the protons simultaneously, as can be seen by comparing the even-even with the odd-odd nuclei. The present study of Eu nuclei implies that the effect of the odd proton is to enhance the odd-even neutron staggering (cf. the isotope chains of $_{64}$Gd and $_{62}$Sm).

The discussion on the odd-even effect of the electric dipole moment (D_0) is based upon microscopic arguments and therefore implicitly suggests that the microscopic contribution (shell contribution) to the dipole moment ($D_0^{\rm shell}$) is large for europium nuclei. This is consistent with the calculations performed by Butler and Nazarewicz [1], which predict no macroscopic ($D_0^{\rm macro} = 0$), and a large shell contribution to the intrinsic dipole moments of the Nd and Sm nuclei.

In summary, the sequence of europium nuclei studied shows a noticeable increase in collectivity: from single-

TABLE II. The measured $B(E1)/B(E2)$ transition rates.

J^π	$\frac{B(E1)}{B(E2)}$ (10^{-6} fm^{-2})	$K_i = K_f$	$B(E2)$ (10^2 e^2 fm^4)	$B(E1)$ (10^{-4} e^2 fm^2)	$\lvert D_0\rvert$ (e fm)
^{148}Eu					
13^-	0.5(2)	11	0.98	0.4(1)	0.036(5)
14^-	0.67(5)	12	0.85	0.57(5)	0.043(3)
16^-	1.2(2)	12	3.5	4.1(7)	0.090(8)
^{149}Eu					
$21/2^+$	0.4(1)	17/2	1.7	0.7(2)	0.09(2)
$25/2^+$	0.75(6)	17/2	6.1	4.6(4)	0.086(4)
$27/2^-$	0.51(15)	11/2	16.7	85(3)	0.095(2)
$29/2^+$	0.43(8)	17/2	9.9	4.3(8)	0.076(8)
$29/2^+$	0.15(2)	17/2	9.9	1.5(2)	0.045(3)
$17/2^-$	0.5(2)	9/2	11	23(6)	0.17(3)
$19/2^+$	0.12(2)	15/2	2.1	0.25(4)	0.018(2)
$19/2^+$	0.23(3)	15/2	2.1	0.48(6)	0.024(2)
$21/2^-$	1.1(4)	9/2	17.4	19(6)	0.14(3)
$23/2^+$	0.15(4)	15/2	7	1.1(4)	0.04(1)
$23/2^+$	1.0(3)	15/2	7	7(2)	0.10(2)
$33/2^+$	1.4(1)	29/2	0.7	1.0(1)	0.06(1)
$37/2^+$	1.1(3)	29/2	3.2	3.5(9)	0.09(2)
^{150}Eu					
17^-	0.18(2)	13	5.4	1.0(1)	0.045(3)
^{151}Eu					
$19/2^+$	0.27(9)	15/2	4.3	1.2(4)	0.052(9)
$23/2^+$	1.5(3)	15/2	15	22(4)	0.18(2)
$27/2^+$	1.8(2)	15/2	23	42(5)	0.23(2)
$31/2^+$	5(3)	15/2	30	160(100)	0.43(15)
$25/2^+$	0.06(3)	17/2	13	0.7(3)	0.034(7)
$29/2^+$	0.5(1)	17/2	21	10(2)	0.11(1)
$33/2^+$	0.9(2)	17/2	28	25(6)	0.17(2)

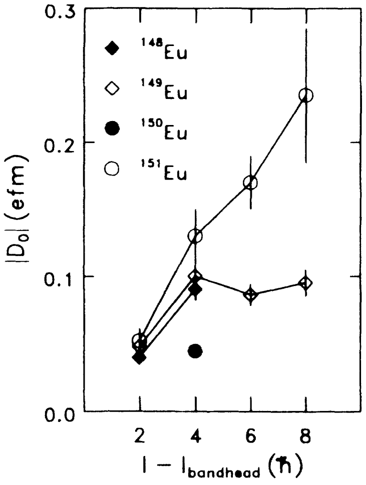

FIG. 3. Averaged $|D_0|$, calculated from the measured $B(E1)$ rates, plotted as a function of the difference in spin between the spin I of the state from which the $E1$ transition decays and the spin of the band head I_{bandhead}.

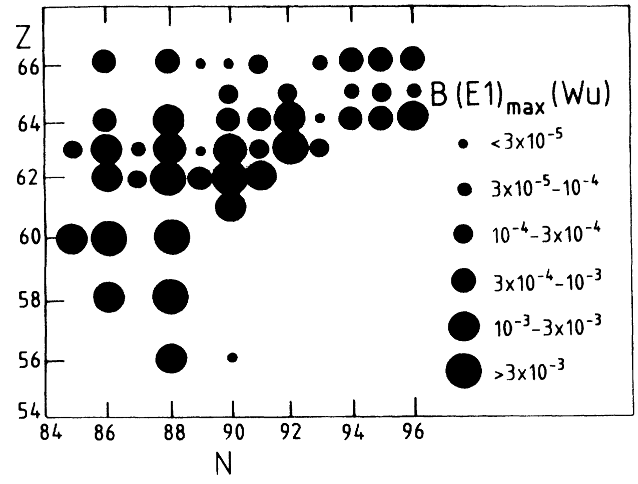

FIG. 4. Largest measured $B(E1)$ rates for nuclei in the lanthanide region. For references to original work of nuclei not discussed in the present paper, see [10] and references therein.

particle-like structures (multi-p-h) in ^{148}Eu to rotational-like structures in ^{151}Eu. In all these nuclei octupole correlations were found. In the single-particle-like nuclei (^{148}Eu and ^{149}Eu) these octupole correlations were evident through their single 3^- phonon coupling to some of the identified multi-p-h states.

In the more collective nuclei (especially ^{151}Eu) octupole correlations are observed in the quasirotational structures of these nuclei. In particular the strongly enhanced $B(E1)$ rates tend to increase with increasing spin. This suggests that in these nuclei an instability towards octupole deformation develops at medium spins. In a large scale study octupole correlations [$B(E1)$ strengths] seem to decrease for odd-even nuclei with respect to even-even nuclei. Odd-odd nuclei like ^{148}Eu and ^{150}Eu have $B(E1)$ strengths, which are even more reduced compared to their odd-even neighbors.

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