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Opposite-parity bands in ^{153}Eu

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Excited states of ^{153}Eu were observed using the ^{150}Nd(^{7}Li, $4n$) reaction at a beam energy of 40 MeV. Two rotational bands with levels of spins up to $\frac{45}{2}\hbar$ were seen; a positive parity band built on the $5/2^+$ ground state, and a negative parity band built on the $5/2^-$ level at 97.5 keV excitation energy. Transitions were also observed from levels in a band built on a $3/2^+$ state at 103.2 keV. Several features of the $5/2^{\pm}$ bands suggest octupole instability or deformation, as may be expected for nuclei in this region. Levels of the same spin but opposite parity are nearly degenerate, and strong electric dipole transitions connect appropriate band members. Other features such as gyromagnetic ratios indicate an interpretation in terms of bands associated with separate orbits in a reflection-symmetric potential.

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In recent years several experimental and theoretical studies have sought to determine whether nuclei in certain regions of the nuclear chart have stable intrinsic octupole deformations. A recent review [1] refers to much of this effort. Some suggestions of reflection asymmetry in even-even light actinides [2,3] and in even-even neutron-rich lanthanides [4,5] are provided by observations of opposite parity sequences of levels which interlock in spin over certain ranges of excitation energy and which have large electric dipole ($E1$) transition rates for appropriate transitions between them.

In odd-A nuclei a reflection-asymmetric mean field would give rise to intrinsic states of mixed parity, resulting in nuclei which exhibited parity doublets, and associated rotational bands in nuclei with sufficient total deformation. Normally, appropriate levels in parity doublet bands would be connected by strong $E1$ transitions with strength corresponding to the size of the intrinsic-frame static $E1$ moment. Early experimental evidence [6,7] suggested the existence of parity doublet bands in ^{219}Ac and ^{223}Th. More recent experiments [8,9] showed similar features in ^{151}Pm, although in that nucleus measurements on magnetic dipole ($M1$) transitions revealed differences in the magnetic properties of the separate positive and negative parity sequences and gave g factors in agreement with those predicted for expected reflection-symmetric band structures.

In the odd-Z lanthanides near $N = 90$, $Z = 60$, independent particle motion in an axial- and reflection-symmetric potential leads [10] to orbits in the intrinsic frame with quantum numbers $\Omega^\pi = 1/2^{\pm}, 3/2^{\pm}$, and $5/2^{\pm}$ lying close together and close to the Fermi level. (The number Ω gives the projection of angular momentum on the symmetry axis, and π the parity.) If the potential becomes octupole deformed, intrinsic states no longer have good parity and the nuclei may exhibit parity doublet bands. Recent microscopic calculations [11] predict that in ^{151}Pm and ^{153}Eu the mixing is strong only for the low-lying intrinsic-frame states with $\Omega = 1/2$, and that the low-lying bands with $\Omega^\pi = 5/2^{\pm}$ can be described predominantly within a reflection-symmetric model, rather than as parity-doublet bands. The bands observed in ^{151}Pm have $\Omega^\pi = 5/2^{\pm}$ and can be identified with the states discussed theoretically. The observation that their g factors agree with those anticipated for reflection-symmetric intrinsic states supports the theoretical predictions. However, the strong and consistent $E1$ rates measured for transitions between levels in the opposite parity sequences, and the close relative level spacings, suggest the validity of a reflection-asymmetric approach. It is important to resolve this problem in the odd-Z lanthanides and this Rapid Communication describes experiments done to clarify the description of opposite-parity bands in ^{153}Eu.

^{7}Li particles of energy 40 MeV from the accelerator at the Daresbury Laboratory bombarded a Nd target of thickness 9 mg/cm^2 enriched to 92.4% in the ^{150}Nd isotope. An array of 16 Compton-suppressed Ge detectors was used to observe γ-γ coincidences in evaporation residues resulting from fusion reactions, and a total of 2×10^7 γ-γ coincidence events was recorded. The largest fraction of the residues consisted of ^{153}Eu nuclei, with small fractions resulting from the $(p, 4n)$ and $5n$ exit channels which left ^{152}Sm and ^{152}Eu nuclei, respectively. The energies of γ rays depopulating the low-lying levels of ^{153}Eu are known from early work [12], and levels in rotational bands with $5/2^{\pm}$ bandheads and spins up to $\sim 25/2$ are known from previous [13] fusion-evaporation experiments. The partial decay scheme for yrast and near-yrast levels in ^{153}Eu was extended using known γ-ray energies as starting points, and the E_γ-E_γ coincidence matrix generated from the events recorded. A γ-ray spectrum obtained in coincidence with the 330.0 keV, $15/2^+ \rightarrow 11/2^+$, transition is shown in Fig. 1 to indicate the quality of the data. From gated spectra similar to Fig. 1 γ-ray energies and intensities were used to construct the decay scheme shown in Fig. 2. Several levels above those shown in Fig. 2 were identified in each of the $5/2^+$ and $5/2^-$ bands, the most likely spins of the uppermost levels identified being 45/2 in each of the sequences.

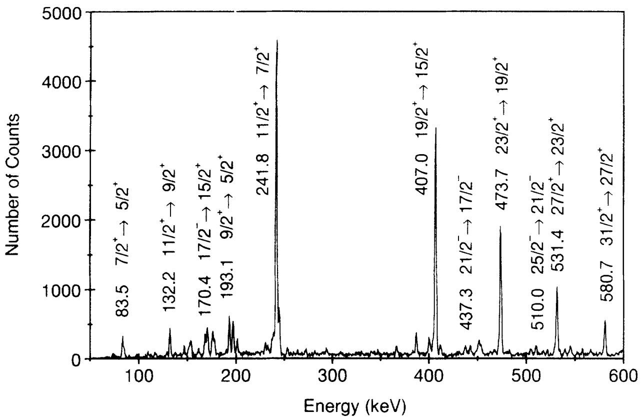

FIG. 1. The spectrum of γ rays in coincidence with the 329.9 keV, $15/2^+$ to $11/2^+$ transition in ^{153}Eu. Prominent peaks are labeled with their energies in keV and their location in the energy scheme of Fig. 2.

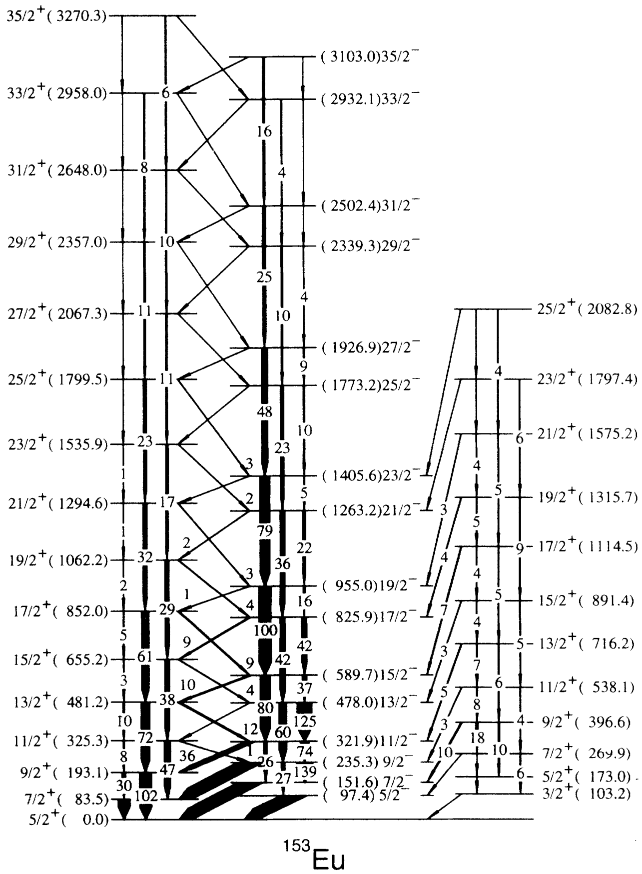

FIG. 2. Partial decay scheme for ^{153}Eu. The arrows are labeled with the intensity of the observed γ-ray transition relative to that of the 365.3 keV, $19/2^-$ to $15/2^-$ transition, taken to be of strength 100 units. Errors on the intensities range from about 25% for weak lines to about 10% for strong lines. Errors on level energies range from ± 0.1 keV for low levels to ± 0.2 keV for the highest levels shown.

They have been omitted for clarity, and since intraband transitions involving them were too weak to be observed they will not be discussed further. The γ-ray energies and relative efficiencies were calibrated using known cascades in ^{152}Sm which were present in the data themselves. Two low-energy points were added using calculated gated intensities for the lines of energies 83.4, 109.7, and 193.1 keV made using known [12] internal conversion coefficients and known γ-ray branching ratios for decay of the 1193.1 keV level.

The spin and parity assignments of the new levels observed are based on their modes of decay. In the ground-state positive parity band, firm spin assignments exist up to the 21/2 level at 1294.6 keV; in the $5/2^-$ band firm spin assignments exist up to the 23/2 level at 1405.6 keV. The 1535.9 keV level is here assigned spin 23/2 and placed in the ground-state band because of its decays to the $21/2^+$, $19/2^+$, and $21/2^-$ levels, and the absence of decays to other states. Similar arguments apply to all the levels shown on the $5/2^\pm$ bands on Fig. 2. In addition, their excitation energies and the branching ratios observed in their γ decays (as seen later) support the placements of the levels into the bands shown. The spins of the states in the sideband built on the $3/2^+$ level at 103.2 keV are also based on the decay patterns of the

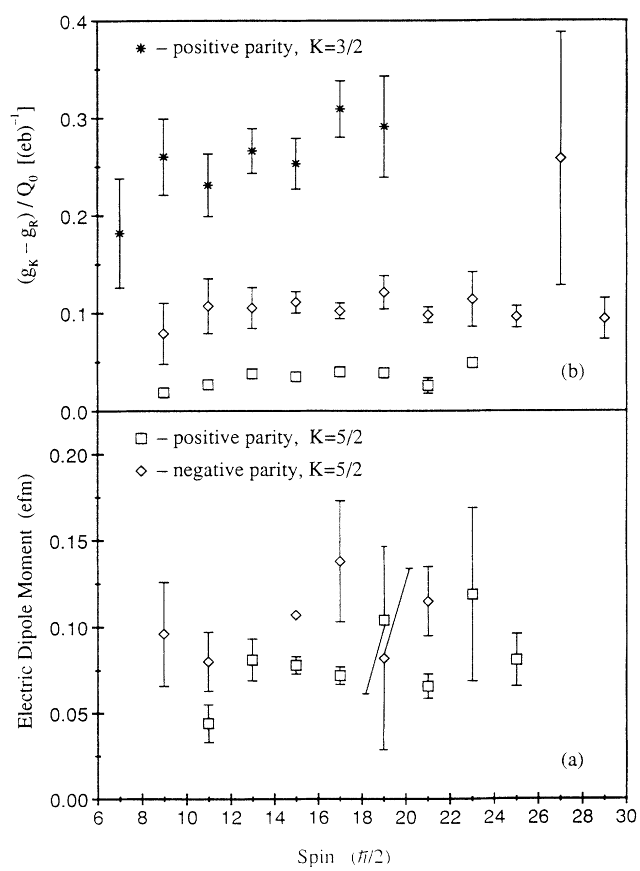

FIG. 3. (a) Intrinsic dipole moments D_0 deduced from $B(E1)/B(E2)$ values obtained from γ-ray branching ratios, plotted against the spin (in units of $\hbar/2$) of the level emitting the γ rays. (b) The size of the parameter $(g_K - g_R)/Q_0$, obtained from within band branching ratios.

levels and the agreement of the measured branching ratios with those expected for transitions within a good rotational band.

Figure 2 shows a level scheme remarkably similar to those seen in ^{151}Pm and ^{223}Th, but more extensive than that known for ^{151}Pm, and with more transition data than known for ^{223}Th. Levels of spin $(n + 1/2)$, with n an even integer, and opposite parity lie close in energy in the $5/2^{\pm}$ bands, although the marked staggering in the negative parity band already indicates a somewhat different structure to that of the ground-state sequence. The ratio of intensities of the $E1$ transitions with spin change $\Delta I = 1$ to the intensities of the $\Delta I = 2$, $E2$, transitions were used to determine the ratio $B(E1; I \to I-1)/B(E2; I \to I-2)$ for levels of spin I in each of the $\Omega^{\pi} = 5/2^{\pm}$ bands, as well as for the $\Omega^{\pi} = 3/2^{+}$ sideband. Absolute $B(E1)$ values were estimated from the $B(E1)/B(E2)$ ratios using in all cases $B(E2)$ values calculated using a constant intrinsic quadrupole moment Q_0 equal to 6.75 e b; that obtained from the measured [12] spectroscopic quadrupole moment of the ground state. The $B(E1)$ values were in turn translated into intrinsic static $E1$ moments D_0 using a model describing rotation of an octupole-deformed core. The information obtained is given in Table I, and the static electric dipole moments extracted for the $5/2^{\pm}$ bands are plotted in Fig. 3(a). The $B(E1)$ values are larger than found normally in medium-weight nuclei and the D_0 of the levels in the $5/2^{\pm}$ bands are constant within the errors and of average size which fits well with the trends observed [14] in this region. The moments D_0 reach a maximum near $Z = 60$, $N = 90$ corresponding to the anticipated maximum in octupole correlation effects in this area of the nuclear chart. These aspects of the data are consistent with octupole deformation, however, the $E1$ transition rates between levels in the $3/2^{+}$ sideband and those in the $5/2^{-}$ band are of comparable size, as Table I shows, suggesting that there is no special relationship between the intrinsic structure of the $5/2^{-}$ band and that of the $5/2^{+}$ band alone.

Strong evidence in favor of a reflection-symmetric description of the intrinsic states of the bands is provided by the intensity ratios of the transitions within each of the separate sequences. The ratio of the intensity of the $E2$, $\Delta I = 2$, crossover transition from a level to that of the mixed $E2/M1$, $\Delta I = 1$, transition is a measure of the parameter $(g_K - g_R)/Q_0$, where g_K and g_R are orbital and rotational g factors, respectively. The size of this parameter is plotted in Fig. 3(b) for the negative and positive parity spin 5/2 bands. Within the errors the values are consistent within each band but they differ between the bands. These are the same features as observed in ^{151}Pm, and there is also a strong suggestion of staggering in the $5/2^{-}$ band in the manner appropriate [15] to a signature-split band based on the $\Omega = 5/2$ orbital arising from the $h_{11/2}$ spherical set of states. Taking Q_0 equal to 6.75 e b for all levels, $g_R = 0.4 \approx Z/A$ and the positive value of $(g_K - g_R)$, the calculated values of the magnetic mo-

TABLE I. Column 6 gives $B(E1)/B(E2)$ values for intraband transitions in ^{153}Eu deduced from the observed γ-ray intensity ratios given in column 5. The final column gives D_0 values extracted assuming the $5/2^{\pm}$ bands constitute parity doublet bands.

E_i (keV)	$I_i\pi_i$	$E_\gamma(E1)$ (keV)	$E_\gamma(E2)$ (keV)	$I(E1)/I(E2)$	$B(E1)/B(E2)$ (10^{-7}fm^{-2})	D_0 (e fm)
325.3	$11/2^+$	90.0	241.8	0.025(6)	0.220(56)	0.044(11)
481.2	$13/2^+$	159.3	288.1	0.166(25)	0.629(93)	0.081(12)
655.2	$15/2^+$	177.2	329.9	0.099(6)	0.536(35)	0.078(5)
852.0	$17/2^+$	262.3	370.8	0.146(10)	0.438(31)	0.072(5)
1062.2	$19/2^+$	236.3	407.0	0.135(57)	0.88(37)	0.104(44)
1294.6	$21/2^+$	339.6	442.6	0.105(11)	0.350(35)	0.066(7)
1535.9	$23/2^+$	272.7	473.7	0.121(51)	1.10(47)	0.119(50)
1799.5	$25/2^+$	393.9	504.9	0.121(23)	0.501(95)	0.081(15)
235.3	$9/2^-$	151.8	137.9	13.8(4.2)	1.52(47)	0.096(30)
321.9	$11/2^-$	128.8	170.3	1.39(30)	0.72(15)	0.080(17)
589.7	$15/2^-$	108.5	267.8	0.121(34)	1.01(28)	0.107(30)
825.9	$17/2^-$	170.7	347.9	0.203(52)	1.60(41)	0.138(35)
955.0	$19/2^-$	103.0	365.3	0.012(8)	0.55(35)	0.082(52)
1263.2	$21/2^-$	201.0	437.3	0.069(12)	1.05(19)	0.115(20)
396.6	$9/2^+$	245.0	223.6	0.96(33)	0.282(95)	
538.1	$11/2^+$	302.8	268.2	0.76(14)	0.293(52)	
716.2	$13/2^+$	394.3	319.6	0.91(15)	0.382(61)	
891.4	$15/2^+$	413.4	353.3	0.511(42)	0.307(25)	
1114.5	$17/2^+$	524.8	398.3	1.31(12)	0.701(64)	
1315.7	$19/2^+$	489.8	424.3	0.468(61)	0.422(55)	
1575.2	$21/2^+$	620.2	460.7	0.49(14)	0.329(96)	

ments of the $5/2^+$ and $5/2^-$ bandheads [using observed average values for $(g_K - g_R)/Q_0$ of 0.033(3) $(e\,\mathrm{b})^{-1}$ for the $5/2^+$ band and 0.103(8) $(e\,\mathrm{b})^{-1}$ for the $5/2^-$ band] are $1.41(14)\mu_N$ and $2.24(18)\mu_N$, respectively. These moments are in reasonable agreement with the directly measured [12] values of $1.533(1)\mu_N$ and $3.22(23)\mu_N$. They are also in agreement with predictions when a reflection-symmetric mean field is used to calculate the most probable intrinsic proton states of the two rotational bands. These intrinsic states are the $5/2^+$ [413] and $5/2^-$ [532] Nilsson orbitals, which give bandheads with predicted moments of near $1.5\mu_N$ and near $2.6\mu_N$, respectively, using both a modified oscillator potential [16] and a Woods-Saxon potential [17]. The $(g_K - g_R)/Q_0$ parameters for the $3/2^+$ sideband are also constant within errors, and have an average value of 0.272(22) $(e\,\mathrm{b})^{-1}$ corresponding, with the same procedure as before, to a $3/2^+$ bandhead magnetic moment of $2.25(18)\mu_N$, also in agreement with the directly measured [12] $2.04(1)\mu_N$.

The conclusion from the present experiments is that the spin 5/2 opposite parity bands in ^{153}Eu are well described by the reflection-symmetric Nilsson model. This is in agreement with the microscopic calculations quoted [11] earlier which indicate little parity mixing of the spin 5/2 intrinsic states. The present extensive data set suggest this conclusion for ^{153}Eu. It is very likely that it is also true for ^{151}Pm in view of the similarity between the opposite parity bands in that nucleus and in ^{153}Eu. Common features are also seen in ^{223}Th, where staggering in the negative parity band occurs and the limited data on $M1$ transition rates also suggest a difference in the magnetic properties of the opposite parity bands. The large strengths of the $E1$ transitions in ^{151}Pm and ^{153}Eu distinguish the bands seen there from those in most other odd-A nuclei. It has been shown [18] that large enhancements of $E1$ rates are possible when octupole correlations are substantial. The strongest $E1$ rates consistently occur in nuclei where octupole correlations are expected to be strongest. It remains a challenge to understand the distribution of $E1$ strength in the neutron-rich lanthanides and the light actinides.

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