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Evidence for reflection asymmetric shape in the nucleus $^{151}_{61}\mathrm{Pm}_{90}$

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The occurrence of multiple parity doublets, enhanced $E1$ transitions between parity-doublet levels, characteristic decoupling parameters for $K=\frac{1}{2}$ parity-doublet bands, and hybridization of the nuclear magnetic moments are sought as evidence for reflection asymmetric shape in odd-Z odd-mass rare-earth nuclei. Specific results consistent with such an assumption are presented for the nucleus $^{151}_{61}\mathrm{Pm}_{90}$. Suggestions are offered for further experiments following a review of available information on other nuclei of the region.

The searches for spectroscopic evidence for the occurrence of reflection asymmetric shapes in the lighter actinides have been extensively pursued since the theoretical consequences of such shapes were explicitly pointed out.[1,2] For the even-even nuclei the characteristic feature is the appearance of the interlaced $K^{\pi}=0^{\pm}$ band levels connected by fast $E1$ transitions. For the odd-mass nuclei the appearance of parity-doublet (PD) bands,[3] whose levels are connected with fast $E1$ transitions, provides the primary evidence for reflection asymmetric octupole deformation. Enhanced $E3$ transition rates do provide a more direct measure of these properties; however, practically no experimental information on these rates is as yet available in the region under consideration. The magnetic moments for the parity doublets are expected[4,5] to approach a single hybridized value. Further, in such a picture, the $K^{\pi}=\frac{1}{2}^{\pm}$ parity-doublet bands are expected[4,5] to have decoupling parameters of equal magnitudes but opposite sign. More recently[6-8] the reversal of the odd-even staggering of the differential radii has also been related to octupole deformations.

Two years ago we presented[9] physical arguments for expecting similar structures for similar nucleon (proton for the actinides and neutron for the rare earths) numbers in the context of evolution towards stable octupole deformation at higher spin in even-even rare-earth nuclei and had suggested instead an extended region from $_{56}$Ba to $_{64}$Gd for such investigations. Detailed evidence for the overlapping opposite parity $K^{\pi}=0^{\pm}$ bands has since been presented for ^{144,146}Ba (Ref. 10), ^{150}Sm (Ref. 11), ^{146,148}Nd (Ref. 12), and ^{146}Ce (Ref. 13). Also, same-K opposite parity band pairs (interpreted as parity doublets) with connecting fast $E1$ transitions have been reported[14] in the doubly odd ^{152,154}Eu isotopes with additional evidence from the observed differential radii of the $_{63}$Eu isotopic chain. However, the odd-mass nuclei of this region have not been investigated so far. This situation contrasts sharply with the intense activity involving the odd-mass actinides.[15-25] We have undertaken a detailed examination of the evidence for octupole deformations in the odd-mass and the odd-odd rare-earth nuclei and present here the first report of multiple parity doublets identified in an odd-mass nucleus of this region. We also examine the $E1$ transition rates between levels constituting the parity doublets and between levels not connected as such doublets. Further, our study considers the evidence from the observed decoupling parameters for the $K=\frac{1}{2}$ bands and the magnetic moments. Detailed results are presented for the nucleus ^{151}Pm along with a survey of the other odd-mass odd-Z nuclei of the region.

The experimental results[26-28] for the $A=151$ mass chain, recently reevaluated for *Nuclear Data Sheets*,[29] form the basis of our study. The low-energy level scheme for the nucleus ^{151}Pm is shown in Fig. 1, wherein we have grouped together the pair of opposite parity same-K bands. Even though, in the presence of parity mixing, the asymptotic quantum numbers of the Nilsson scheme are no longer good quantum numbers, we continue using these as labels for individual bands, remembering that the indicated configuration is the major component of the level. We identify four sets of parity doublets involving eight bands and list three other high-energy positive-parity bands with no available negative-parity counterparts. The level scheme[30] of the nucleus ^{155}Eu is shown in Fig. 2. For estimating the $I=\frac{1}{2}$ level energy for the $\frac{1}{2}^{-}[550]$ band with respect to the observed 747-keV $\frac{3}{2}^{-}$ level in ^{151}Pm we have adopted the band parameters from the known spectrum of the neighboring nucleus ^{155}Eu. The bandhead of the $\frac{7}{2}^{-}[523]$ band with respect to the known 1205-keV $\frac{11}{2}^{-}$ level in ^{151}Pm is estimated using the average inertial parameter from the ground bands in the odd-mass Ho isotopes. The strength of the $\frac{5}{2}^{+}[402]$ configuration in this region is believed[31] to be fragmented over a number of $\frac{5}{2}^{+}$ states.

We find an average splitting energy of 233 keV for the four PD's in ^{151}Pm. This may appear to be rather high; however, as emphasized in the formulation of the PD theory,[2] the size of the energy splitting in a doublet by itself does not provide a measure of the amount of octupole deformation or its stability. In fact, if the doublet splitting were assumed as the guiding criterion, one may be tempted to couple the $\frac{1}{2}^{+}[411]$ band starting at 852 keV with the 752-keV $\frac{1}{2}^{-}[550]$ band to form a PD thus reducing the average splitting by 56 keV. However, as discussed below, the consideration of the decoupling param-

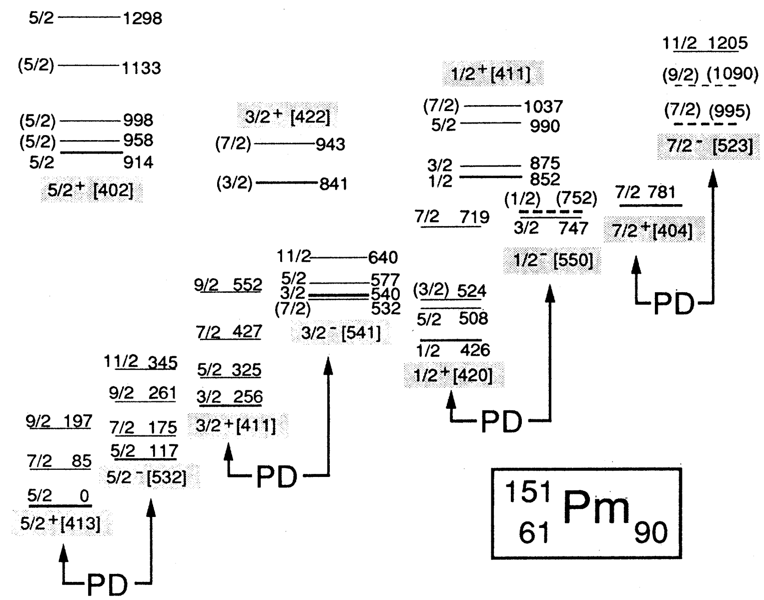

FIG. 1. The band structure in the level scheme of the nucleus $^{151}_{61}Pm_{90}$; the proposed $K^{\pm}$ parity-doublet bands (labeled PD) are shown connected. The dashed lines indicate the extrapolated position of the rotational levels not experimentally identified so far.

eters for the $K=\frac{1}{2}$ bands, which form a more demanding criterion, requires the doublet structure as shown in Fig. 1.

Looking at the PD energy splitting systematics over the odd-Z, odd-mass region, we find that the $K^{\pi}=\frac{5}{2}^{\pm}$ doublet comprised mainly of the [413] and [532] configurations has been seen in practically every nuclide with energy splitting ranging from 1.2 keV in ^{157}Tb to about 200 keV in ^{153}Eu. It appears as the lowest configuration pair in $_{61}$Pm as well as $_{63}$Eu isotopes with $N\geq 90$. Wherever measured, the $E1$ transition rates connecting the various members of this PD are enhanced by at least an order of magnitude in comparison with the non-PD transitions. The $K^{\pi}=\frac{3}{2}^{\pm}$ PD has a moderate splitting only in ^{151}Pm. In all other nuclei, including ^{153}Pm, the two bands are separated by $\gtrsim 500$ keV. The $K^{\pi}=\frac{7}{2}^{\pm}$ band's doublet has been observed in ^{151}Pm, ^{155}Eu, and the lighter Tb and Ho isotopes. The $K^{\pi}=\frac{1}{2}^{\pm}$ PD with [420] and [550] as the main configurations is observed only in the ^{151}Pm and ^{155}Eu nuclides. The $K^{\pi}=\frac{7}{2}^{\pm}$ and the $K^{\pi}=\frac{1}{2}^{\pm}$ doublets, expected both in ^{153}Pm and ^{153}Eu, have not been identified so far, and

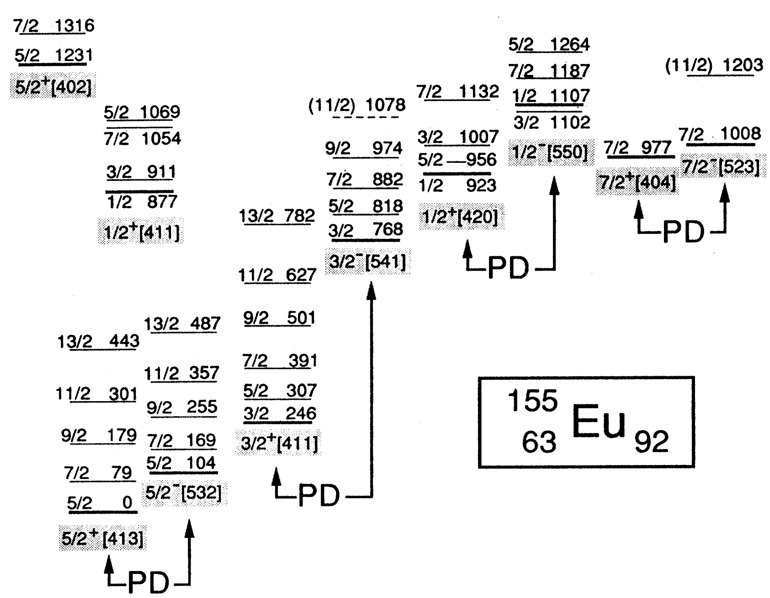

FIG. 2. The corresponding structure in the level scheme of the nucleus $^{155}_{63}Eu_{92}$ for comparison to that shown in Fig. 1 for the nucleus ^{151}Pm.

should be looked for in further experiments.

The decoupling parameter "a" for the $K=\frac{1}{2}$ bands can be evaluated from the experimental level energies by fitting them with the formula

$$E(I)=E_0+A[I(I+1)+a(-)^{I+1/2}(I+\tfrac{1}{2})]+\cdots . \quad (1)$$

An important signature[2] of the octupole mode is that the opposite parity bands of a PD have decoupling parameters of equal magnitude but opposite sign. In the case of the odd-mass actinides,[16-25] the experimental values of the decoupling parameters of the positive- and negative-parity bands of $K^\pi=\frac{1}{2}^\pm$ PD's are seen to converge towards a common $|a|$, thus providing evidence of hybridization expected for stable octupole deformations. In no case, however, do the two values achieve nearly the same absolute value. In ^{151}Pm, as well as in ^{155}Eu, two $K^\pi=\frac{1}{2}^+$ bands, labeled as $\frac{1}{2}^+$[420] and $\frac{1}{2}^+$[411] in the figures, have been identified. The $\frac{1}{2}^+$[420] has also been observed in ^{153}Pm, while the $\frac{1}{2}^+$[411] has been identified in the $N=92$ $_{65}$Tb and $_{67}$Ho isotopes. The calculated[36] decoupling parameters for these Nilsson orbitals for $\delta=0.30$ are $+1.06$ and -0.88, respectively. Experimentally, using the lowest three observed level energies, we find $a=+1.22$ for the 426-keV based band and $a=-0.51$ for the 852-keV based band in ^{151}Pm, with similar values in the other nuclei. The two negative-parity bands expected in this region are $\frac{1}{2}^-$[550] and $\frac{1}{2}^-$[541] with the calculated[36] decoupling parameters -5.6 and $+3.1$, respectively. Experimentally the $\frac{1}{2}^-$[550] band has been observed only in ^{155}Eu with $a=-1.1$, and only its $\frac{3}{2}^-$ rotational level has been identified at 747 keV in ^{151}Pm. The $\frac{1}{2}^-$[541] band has been identified in the $N=90$ $_{65}$Tb isotone and also in $N=90$ and $N=92$ $_{67}$Ho isotones, with $a\sim+1.7$ in all cases. A comparison of the calculated and the experimental decoupling parameters for the four $K=\frac{1}{2}$ bands reveals the approach to the hybridized values expected for octupole shape. Particularly, the values for the negative-parity bands are found to be considerably reduced approaching in magnitude, but with opposite sign, the values found for the positive-parity bands. It stands as an experimental challenge to unambiguously identify the rotational levels for the $\frac{1}{2}$[550] and $\frac{1}{2}$[541] bands, expected to lie in the 600–1200 keV excitation energy range in ^{151}Pm, ^{153}Pm, ^{153}Eu, and ^{155}Eu.

Another significant criterion for the existence of stable octupole deformation in odd-A nuclei is a measure of the $E1$ transition rates. In the case of octupole deformed actinides the $E1$ transition rates between members of reflection asymmetric PD bands are enhanced by a factor of $\sim 10^2$ relative to normal $E1$ rates between Nilsson states. Several transition rates of interest has been measured[29] for levels in ^{151}Pm. The experimental $E1$ transition rates connecting PD's and also not connecting such doublets are listed in Table I. The 1297.682-keV $\frac{5}{2}^+$ level, with no given configuration assignment, provides most of the non-PD data; this state is likely to have a part of the fragmented strength of the $\frac{5}{2}^+$[402] configuration which, in this region, is distributed[31] among various $\frac{5}{2}^+$ levels spread over ~ 0.5 MeV range. From Table I we clearly see that the $E1$ transitions connecting the parity-doublet states (labeled "Yes" in the last column) are faster by an order of magnitude or more, than the $E1$ transitions connecting non-PD states.

The magnetic moments of the $K^\pm$ parity-doublet bandheads are predicted[2,4,5] to be identical in the extreme limit of rigid octupole deformation with an infinite barrier between the mirror minima. In the parity mixing of the reflection symmetric Nilsson orbitals, the experimental magnetic moments should approach the hybridized mean value.[2] The calculated values, respectively, for the $\frac{5}{2}^+$[413] and the $\frac{5}{2}^-$[532] bandheads are given as 0.9 nm and 3.1 nm by Mottelson and Nilsson,[32] and as 1.42 nm and 2.65 nm by Ekström and Lamm.[33] The measured[34] value 1.8(2) nm for the $\frac{5}{2}^+$ ground state of ^{151}Pm is seen to be approaching the expected 2.0 nm hybridized value for the $K^\pi=\frac{5}{2}^\pm$ bands. It will be of a great interest to measure the magnetic moment of the 117-keV 89-ps $\frac{5}{2}^-$ excited state in ^{151}Pm in this context. Alternatively, a measurement of the 5.4-m $\frac{5}{2}^-$ ground state of the isotopic ^{153}Pm is of equal, or even more, interest in that this is possibly the only nucleus wherein $\frac{5}{2}^-$[523] appears as the ground-state configuration.

We have, so far, discussed the level schemes of the $N\geq 90$ odd-Z nuclides. It is of interest to examine the $N=88$ odd-A isotones to see if the features related to octupole deformation discussed above persist in the borderline nuclei. The only possible parity doublet, discernible[34] in $N=88$ odd-A nuclei, may be constituted from the $\frac{7}{2}^+$[404] orbital and the close-lying $\frac{7}{2}^-$ negative-parity band (NPB). They appear[35] as the $\frac{7}{2}^+$ ground state and the 270.2-keV $\frac{7}{2}^-$ state in ^{149}Pm. The magnetic moments of the two states are 3.3(5) nm and 2.23(11) nm, respectively, permitting their classification as a PD. However, the $E1$ transition rate for the transition connecting the $\frac{7}{2}^-$ to the $\frac{7}{2}^+$ ground state (1.99×10^{-6} W.u.) is even slower than the $E1$ transition rate (2.3×10^{-5} W.u.) for the 270.2-keV $\frac{7}{2}^-$ decay to the 211.3-keV $\frac{5}{2}^+$ level. Thus, presently, no evidence is available for the octupole deformation in ^{149}Pm or in any other $N=88$ odd-A nuclide based on the criteria adopted here.

In summary we conclude that the proposed parity doublets, the enhanced $E1$ transition rates connecting the PD levels, decoupling parameters for the $K=\frac{1}{2}^\pm$ bands, which are nearly equal in magnitude but opposite in sign, and the hybridized magnetic moment values for the parity mixed orbitals, all suggest the characterization of ^{151}Pm as octupole deformed. Considering the evidence presented here for the odd-Z nuclei ^{151}Pm and ^{155}Eu, and noting the similarities of the available spectroscopic information for the nucleus ^{153}Pm with them, we suggest ^{153}Pm as a promising candidate for a similar octupole structure. Detailed spectroscopy, including lifetime measurement of the excited states and in particular a measurement of the ground-state magnetic moment of ^{153}Pm, will be of considerable experimental interest in this context. We have further suggested experimental identification of the $\frac{1}{2}$[550] and $\frac{1}{2}$[541] levels in these nuclei to search for examples of decoupling parameters with nearly equal but opposite sign. Experimental identification of

TABLE I. Experimentally measured transition rates $B(E1)$ in Weisskopf units (W.u.) for $E1$ transition in ^{151}Pm; the last column indicates whether the involved states belong to a parity doublet (PD) or not, as proposed in this study.

Initial state		Final state		E_γ	$B(E1)$	
E_i (keV)	Configuration	E_f (keV)	Configuration	(keV)	(W.u.)	PD
116.794	$\frac{5}{2}^-[532]$	85.12	$\frac{7}{2}^+\ \frac{5}{2}[413]$	31.67	8.4×10^{-4}	Yes
116.794	$\frac{5}{2}^-[532]$	0.0	$\frac{5}{2}^+[413]$	116.80	1.4×10^{-3}	Yes
175.075	$\frac{7}{2}^-\ \frac{5}{2}[532]$	85.12	$\frac{7}{2}^+\ \frac{5}{2}\ [413]$	89.96	$>2.0\times10^{-4}$	Yes
175.075	$\frac{7}{2}^-\ \frac{5}{2}[532]$	0.0	$\frac{5}{2}^+[413]$	175.07	$>1.2\times10^{-4}$	Yes
255.692	$\frac{3}{2}^+[411]$	116.79	$\frac{5}{2}^-[532]$	138.89	2.7×10^{-5}	No
852.994	$\frac{5}{2}^{(+)}$	116.79	$\frac{5}{2}^-[532]$	736.23	$>3.6\times10^{-6}$	No
1297.682	$\frac{5}{2}^{+}$[a]	746.55	$\frac{3}{2}^-\ \frac{1}{2}[550]$	551.1	2.0×10^{-8}	No
1297.682	$\frac{5}{2}^+$	577.40	$\frac{5}{2}^-\ \frac{3}{2}[541]$	720.3	1.8×10^{-8}	No
1297.682	$\frac{5}{2}^+$	532.06	$\frac{7}{2}^-\ \frac{3}{2}[541]$	765.4	9.7×10^{-8}	No
1297.682	$\frac{5}{2}^+$	175.08	$\frac{7}{2}^-\ \frac{5}{2}[532]$	1122.63	7.3×10^{-7}	No
1297.682	$\frac{5}{2}^+$	116.79	$\frac{5}{2}^-[532]$	1180.89	2.1×10^{-6}	No

[a]The 1297.682-keV $\frac{5}{2}^+$ may have a part of the fragmented strength of the $\frac{5}{2}^+[402]$ configuration.

the $K^\pi=\frac{7}{2}^\pm$ band levels is also of interest. Studies of the differential radii for the Pm isotopic chain are needed to confirm whether the odd-even reversal noted[6,14] for the Eu isotopic chain persists in the $Z=61$ nuclei. In conclusion, the present characterization of ^{151}Pm as octupole deformed, taken in conjunction with the recent[11-14] evidence for similar shapes in even mass nuclei of the region, support the existence of a region of octupole deformation in the $A=150$ neighborhood.

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