Existence of intrinsic reflection asymmetry at low spin in odd and odd-odd mass nuclei in the Pm/Eu region

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The low-spin features of odd-mass nuclei in the $Z \sim 62$, $N \sim 90$ region, for which stable octupole deformation has been previously suggested, are studied without introducing the static intrinsic reflection asymmetry (SIRA). Calculations using a Woods-Saxon potential and taking into account the Coriolis mixing show that most properties can be described in this approximation. Furthermore, the calculated polarization energies of octupole-driving orbitals are not large enough to support the existence of SIRA at low spin in this region.

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I. INTRODUCTION

The structure of odd and odd-odd nuclei with $Z \sim 62$ and $N \sim 90$ has attracted great interest recently, mainly in connection with the possibility of static intrinsic reflection asymmetry (SIRA) [1–3]. Important evidence for this phenomenon is the presence of parity doublets (PD's) [4,5]. In odd-A and odd-odd lanthanide nuclei, PD's have been suggested in ^{151}Pm [1,2,6,7], $^{152-156}$Eu [3,8–10], ^{153}Sm [11], and ^{155}Gd [11]. However, the recent calculations [12] of nuclear ground-state masses and deformations (Fig. 1) performed through wide regions of nuclei do not reveal the existence of stable odd-multipole deformations (further octupole) in the ground states of these nuclei. Similar results have been obtained in other calculations [13] restricted to even-even nuclei, but applied also at $I \neq 0$. Thus, there appears to be an inconsistency between calculations and experiment. The question is then whether too far-reaching conclusions have been drawn from the experimental data or if there is some important error or some important ingredient missing in the calculations. Let us point out that for a more complete description, a model starting from either no octupole deformation [14,15] or static octupole deformation [5] should only be considered as a basis. With appropriate coupling terms, intermediate situations can be described in both cases. Then, the important question is, however, which basis states are most convenient in the sense that they have as large overlap as possible with the more complete solutions.

In the present paper, we will discuss some features related to this question. We will thus investigate if the polarization energy of the odd particle may make special configurations of odd nuclei in this region octupole deformed, even though the even nuclei appear stable towards octupole deformation (Sec. II). Furthermore, we will investigate if properties which have been taken as evidence for octupole deformation could also be understood assuming $\beta_3 = 0$, namely, decoupling parameters (Sec. III), magnetic moments (Sec. IV), and splittings between "parity doublets" (Sec. V).

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II. POLARIZATION EFFECTS DUE TO THE PRESENCE OF UNPAIRED NUCLEONS

Taking into account that the even core is not octupole deformed [see, for example, Fig. 15(b) in Ref. [4] and Ref. [13]], the odd or odd-odd nuclei can get octupole deformed only in the case when unpaired nucleons in

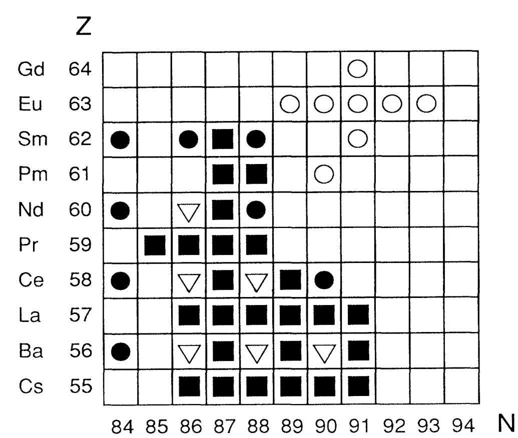

FIG. 1. The nuclei of the Z=55–64, N=84–94 region for which the existence of stable octupole deformation follows from equilibrium deformation calculations [12,13] (solid squares and circles, open triangles) or was suggested based on experimental spectroscopic data (open circles) (see references in [1]). The different symbols are used for marking of nuclei for which calculations show the existence of $\beta_3 \neq 0$ at the ground state (solid squares), both for ground state and high spins (open triangles) and only for high spins (solid circles). The calculation of high-spin equilibrium deformations was performed only for even-even nuclei [13].

specific Nilsson orbitals polarize the shape towards octupole deformation. It is well known that a quasiparticle in a specific Nilsson orbital polarizes the nuclear shapes in such a way that this orbital comes closer to the Fermi level. The driving force can be calculated as proportional to the slope of the quasiparticle energy when drawn versus the relevant deformation parameter [4]. In the case when the driving forces for some orbitals are strong enough to stabilize octupole deformed shapes, we can expect coexistence of SIRA and static intrinsic reflection symmetry (SIRS) shapes in one nucleus since there should be other orbitals which counteract octupole deformation. This situation is observed in octupole transitional nuclei in the actinide region [16]. If the core is octupole soft, then one would expect that a polarization energy around 1 MeV could strongly influence the spectroscopy of odd and, especially, odd-odd nuclei and even induce visible reflection asymmetric deformation in the intrinsic frame.

The tendency towards maximal octupole coupling occurs just above the closed shells, where the (N,ℓ,j) intruder orbitals interact with the $(N-1,\ell-3,j-3)$ normal-parity orbitals through the octupole component in the nuclear Hamiltonian [17]. The strongest shell corrections driving towards $\beta_3 \neq 0$ are present where the Fermi surface penetrates the interaction region between the $\Delta j = \Delta\ell = 3$ orbitals. At spherical shape the strongly octupole interacting subshells, i.e., $\nu i_{13/2}$-$\nu f_{7/2}$ and $\pi h_{11/2}$-$\pi d_{5/2}$, are about 2 MeV apart (see Ref. [18]). With increasing quadrupole deformation, orbitals belonging to the unique-parity subshells approach the normal-parity orbitals which have the same Ω (eigenvalue of j_z) quantum number. For a unique-parity state both j and ℓ are approximately good quantum numbers even at large deformations. This is not true for normal-parity states which are strongly mixed by the quadrupole interaction. Due to this fragmentation the simple picture of two interacting j shells is no longer valid and as a consequence all the states of normal parity with the same Ω values are coupled by the octupole interaction. The single-particle orbitals closest to the Fermi level for protons and neutrons as functions of octupole deformation β_3 at the β_2, β_4 deformations corresponding to ^{153}Eu and ^{153}Sm nuclei, respectively, are presented in Fig. 2. The higher order deformations β_5, β_6 were taken as the following functions of β_2, β_3, and β_4 [13]:

$$\begin{aligned} \beta_5 &= \beta_3\left(0.177\beta_2 + 0.655\beta_4 - 0.0352\beta_2^2 + 0.0089\right), \\ \beta_6 &= -0.2215\beta_4^2 + 0.1055\beta_3^2 + 0.1476\beta_2\beta_4 - 0.0285\beta_2^3. \end{aligned} \tag{1}$$

As a result, our calculations are performed along the path minimizing the liquid-drop energy. In Fig. 2, we can see that there are some proton and neutron orbitals which couple strongly through the Y_{30} operator.

We have calculated the polarization energy of the odd particle which in the BCS approximation simply corresponds to the quasiparticle energy

$$E_\nu = \sqrt{(e_\nu - \lambda)^2 + \Delta^2}. \tag{2}$$

The single-particle energy is given by e_ν, λ is the Fermi energy, and Δ is the pairing gap. The pairing gap and Fermi energy were calculated using the Lipkin-Nogami method [19]. In Fig. 3, the calculated quasiparticle energies are drawn for some octupole coupled orbitals in ^{153}Eu along the same β_3 path as in Fig. 2.

For $Z = 63$, corresponding to ^{153}Eu, it is evident that the two $\Omega = 5/2$ states, 5/2[532] and 5/2[413], are close to the Fermi level for small β_3 and that they slope slightly

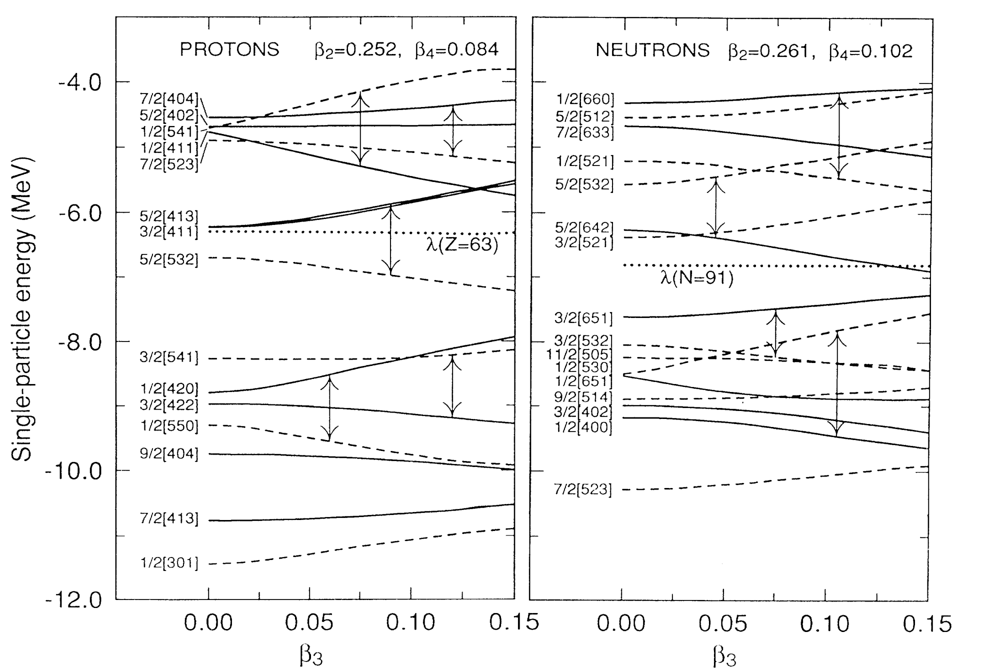

FIG. 2. Single-proton and single-neutron orbitals of the deformed Woods-Saxon potential drawn as functions of octupole deformation β_3 calculated with "universal parameters" for ^{153}Eu ($Z = 63$) and ^{153}Sm ($N = 91$), respectively. The quadrupole and hexadecapole deformation parameters are chosen according to Ref. [12]. Negative-parity orbitals are indicated by dashed lines, positive-parity orbitals by solid lines. Calculated Fermi energies are displayed by dotted lines. Single-particle levels are labeled by the dominant components of wave function at $\beta_3 = 0$. Some orbitals which couple strongly through the Y_{30} operators are connected by arrows.

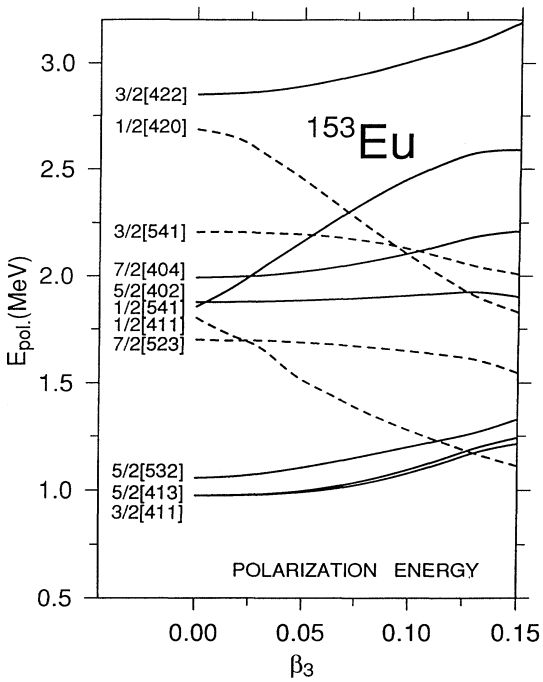

FIG. 3. Polarization energy, calculated as the quasiparticle energy, for ^{153}Eu ($Z = 63$) with the odd particle in different orbitals labeled by their asymptotic quantum number for β_3=0. The octupole-driving orbitals are indicated by dashed lines.

away from the Fermi level with increasing octupole deformation, β_3. Thus, the polarization energy will become negative, striving to make the 5/2 states reflection symmetric. Similar results are found in odd-proton ^{155}Eu and ^{151}Pm nuclei. However, some proton orbitals, for example, those with dominant components of 1/2[411] and 1/2[420] at β_3=0, strive to polarize the nucleus towards stable octupole deformation.

The energy gain at $\beta_3 = 0.15$ due to the polarization energy is presented in Table I for all octupole-driving orbitals. For these orbitals, the quasiparticle energy is close to a linear function in β_3, and so it is easy to estimate the energy gain for other values of β_3. For example, we can conclude that there are not any orbitals which for a typical value of octupole deformation in the actinide region,

TABLE I. Octupole-driving orbitals and their polarization energies, $E_{\rm pol}$ (MeV), defined as the energy gain due to the odd particle at $\beta_3 = 0.15$ relative to $\beta_3 = 0$. Orbitals with $E_{\rm pol} < 0.2$ MeV are not shown.

	Odd-proton nuclei				Odd-neutron nuclei	
Orbitals	^{151}Pm	^{153}Eu	^{155}Eu	Orbitals	^{153}Sm	^{155}Gd
1/2[411]	—	0.69	—	1/2[530]	0.74	—
1/2[420]	0.61	0.76	0.62	1/2[521]	0.42	0.44
1/2[541]	1.01	—	0.47	1/2[541]	—	0.33
7/2[523]	0.46	0.16	0.24	1/2[660]	—	0.60
3/2[541]	—	—	0.27	7/2[523]	0.32	—
				7/2[633]	0.31	0.34
				3/2[651]	0.21	—

$\beta_3 = 0.10$, give an energy gain larger than 0.6 MeV. As a result, added to an "even-even" energy surface without octupole minima, it is clear that these orbitals can only polarize the nucleus towards more pronounced octupole softness, but cannot create the deep minima which are necessary to form stable octupole deformed shapes.

Even though no SIRA shapes are formed, the repulsive character of two orbitals with equal Ω, but different parities at β_3=0, points to the possibility of dynamical octupole correlations. For example, the two pairs of proton orbitals (1/2[420],1/2[550]) and (1/2[411],1/2[541]), which are seen to repel each other in Fig. 2, are strongly octupole correlated in the case of SIRS according to the quasiparticle-phonon model [20].

In our simple model, the total polarization energy of unpaired particles in specific two-particle configurations in odd-odd nuclei will be the sum of the proton and neutron quasiparticle energies. The polarization energy for all experimentally assigned low-lying two-quasiparticle states, based on proton orbitals 5/2[413], 5/2[532], and 3/2[411], for odd-odd nuclei in this region is small, since not only are SIRS shapes energetically favorable for these proton orbitals, but also the polarization energy of neutron orbitals is small. As a result, the presence of SIRA shapes in experimentally observed states of odd-odd nuclei appears questionable.

For the nuclei considered here, the suggestion of SIRA is mainly based on spectroscopic data. Therefore, we will now compare such data with calculations using the Woods-Saxon potential. The β_2 and β_4 deformation parameters for all nuclei under study are taken from Ref. [12].

III. DECOUPLING PARAMETERS OF THE $K^\pi = 1/2^\pm$ BANDS

In the picture of the SIRA, the $K^\pi = 1/2^\pm$ PD bands are expected [5,21] to have decoupling parameters of equal magnitude but opposite sign. In Refs. [2,3,11] the decoupling parameters of $K^\pi = 1/2^\pm$ bands calculated in the Nilsson potential were compared with experimental ones. It was argued that this comparison revealed the approach of those values to the hybridized values expected for octupole shape. Based on similar arguments, the following PD's have been proposed in $A \approx 150$–155 nuclei: π(1/2[420],1/2[550]) and π(1/2[411],1/2[541]) in odd-proton nuclei ^{151}Pm,^{153,155}Eu; ν(1/2[530],1/2[440]) and ν(1/2[521],1/2[660]) in odd-neutron nuclei ^{153}Sm, ^{155}Gd. However, the experimental values of the decoupling parameters can be extracted only in a few cases (see Tables II, III), and from this point of view the assignments of pairs of Nilsson orbitals as members of PD's seem to be very speculative in most cases. Such assignments are relatively well founded only for two proposed PD's: π(1/2[420],1/2[550]) in ^{155}Eu and ν(1/2[400],1/2[530]) in ^{155}Gd.

Our calculations of decoupling parameters for these orbitals using the Woods-Saxon potential and accounting for hexadecapole deformation (see Tables II, III), but no octupole deformation, reveal that the discrepancy be-

TABLE II. Experimental and theoretical decoupling parameters a in ^{151}Pm, ^{153}Eu, and ^{155}Eu. Experimental values of decouping parameters are taken from [20]. Theoretical values of decoupling parameters are calculated using the Woods-Saxon potential with deformation parameters taken from [12]. For comparison, theoretical values of decoupling parameters calculated using modified oscillator (MO) potential [20] are presented.

Conf.	^{151}Pm			^{153}Eu			^{155}Eu		
	MO	WS	Expt.	MO	WS	Expt.	MO	WS	Expt.
1/2[420]	0.94	1.18	1.21(7)	0.75	1.20	1.44(2)	0.76	1.20	2.24(15)
1/2[550]	-5.56	-4.80		-5.56	-4.96		-5.50	-4.74	-1.79(32)
1/2[411]	-0.76	-0.26	-0.54(2)	-0.66	-0.42		-0.66	-0.24	-1.00(33)
1/2[541]	2.71	1.21		2.21	1.36		2.07	1.43	

tween theory and experiment is relatively small. It is only in the case of the pair π(1/2[420],1/2[550]) in ^{155}Eu that the discrepancy between theory and experiment is large. This pair has decoupling parameters of approximately equal magnitude but opposite sign which SIRA can explain. One should note, however, that the assignment of this pair as a PD is not consistent with the calculation of the polarization energy.

IV. MAGNETIC MOMENTS OF "PARITY DOUBLET" STATES

One of the consequences of the rigid SIRA is that the magnetic moments of PD bandheads with opposite parities are predicted to be identical and approximately the hybridized mean of the values calculated from the reflection symmetric Nilsson orbitals [5,23]. For example, the hybridized magnetic moment, assumed $\langle s_z \rangle = 0$, of PD states with $K = 5/2$ in odd-proton nuclei under study should be equal to 2.08. The fact that the magnetic moments of the 5/2[413] and 5/2[532] bandheads in odd-proton ^{151}Pm, ^{153,155}Eu differ from the Nilsson values in the direction of the hybridized mean has been taken as evidence for SIRA in Refs. [2,3].

However, these values of magnetic moments calculated in the Nilsson or Woods-Saxon models cannot be taken as a reliable indicator since they do not take into account the influence of different types of mixing, mainly the Coriolis interaction. Therefore, it is not surprising that such calculations of magnetic moments within these models [24,25] do not reproduce the experimental values for these nuclei with good accuracy.

Admixtures of vibrational states to low-lying states should be relatively small, and so we can consider the rotor+particle coupling (RPC) model [26] as a suitable tool for the calculation of magnetic moments. The results of our calculations are presented in Table IV. Since different authors used different values of the polarization charge x for the spin gyromagnetic factors $g_s^{\mathrm{eff}} = x g_s^{\mathrm{free}}$ with values varying from $x = 0.6$ [24,25] up to $x = 0.7$ [27], calculations were performed for these two limiting values. The Coriolis interaction was attenuated in some cases as specified in the table. The energies of the rota-

TABLE III. Experimental and theoretical decoupling parameters a in ^{153}Sm and ^{155}Gd. Experimental values of decoupling parameters are taken from [22]. Theoretical values of decoupling parameters are calculated using the Woods-Saxon potential with deformation parameters taken from [12].

Configuration	^{153}Sm		^{155}Gd	
	a_{th}(WS)	a_{expt}	a_{th}(WS)	a_{expt}
1/2[400]	0.13		0.16	0.23
1/2[530]	-0.48	(-0.05)[a]	-0.41	-0.47[b]
1/2[521]	0.24	(0.33)[a]	0.35	0.35
1/2[660]	0.75		0.98	

[a]The confidence of this value is low since the spin value of this band was defined as preliminary.
[b]This value is derived using the 422 keV $1/2^-$ level in ^{155}Gd as the $K^\pi = 1/2^-$ bandhead [22]. The alternative choice is the 451 keV $1/2^-$ level as this bandhead which yields $a = -1.02$.

TABLE IV. Magnetic moments of the different states in the nuclei under study, calculated within the rotor+particle coupling model [26]. Experimental values are taken from Ref. [28]. The calculations are performed for the following combinations of the attenuation factor of Coriolis interaction, χ, and the polarization charge for spin gyromagnetic factors, x: A: $\chi = q$, $x = 0.6$; B: $\chi = q$, $x = 0.7$; C: $\chi = 0.0$, $x = 0.6$; D: $\chi = 0.0$, $x = 0.7$, where $q = 1.0$ for positive-parity states of odd-proton nuclei, $q = 0.65$ for negative-parity states of odd-proton nuclei, and $q = 1.0$ for positive- and negative-parity states of odd-neutron nuclei.

Nuclei	State	Expt.	A	B	C	D
	$5/2^+$5/2[413]	1.8(2) 1.29(3)[a]	1.84	1.86	1.46	1.32
^{151}Pm	$5/2^-$5/2[532]	2.20(14)[a]	2.95	3.12	2.72	2.88
	$3/2^+$3/2[411]	1.77(24)	1.74	1.87	1.67	1.80
	$5/2^+$5/2[413]	1.555(42)	1.50	1.35	1.44	1.29
	$7/2^+$5/2[413]	1.81(6)	1.90	1.78	1.76	1.64
^{153}Eu	$3/2^+$3/2[411]	2.048(6)	1.78	1.92	1.70	1.83
	$5/2^-$5/2[532]	3.22(23) or -0.52(23)	3.06	3.22	2.72	2.87
	$5/2^+$5/2[413]	1.56(10)	1.48	1.32	1.42	1.27
^{155}Eu	$5/2^-$5/2[532]	2.49(27)	2.90	3.07	2.73	2.89
^{153}Sm	$3/2^+$(3/2[651] +3/2[402])	-0.0216(1)	-0.36	-0.42	-0.14	-0.21
	$3/2^-$3/2[521]	-0.2591(5)	-0.24	-0.30	-0.018	-0.15
^{155}Gd	$5/2^+$(3/2[651] +3/2[402])	-0.533(4)	-0.60	-0.69	0.50	0.46

[a]The values determined experimentally in Ref. [6] and their apparent accuracies are strongly dependent on the choices of Q_0 and g_R.

tional bands were not fitted.

As follows from Table IV, the RPC model with the Woods-Saxon potential is able to reproduce the experimental values of magnetic moments assuming $x \sim 0.6$ without introducing the SIRA idea.

V. ENERGY SPLITTING BETWEEN 5/2[413] AND 5/2[532] BANDHEADS IN ODD-PROTON NUCLEI

The diagonal matrix elements of single-particle operator $\hat{\pi}$ determine the energy splitting $E(I^-) - E(I^+)$ within a parity doublet of the odd-mass system in the strong coupling limit [23]. The magnitude of the odd-A parity splitting in the strong coupling limit is always less than or equal to that of the core. The odd-A parity splitting ranges from zero for an equal admixture of parities in the single-particle state to the full core value, $E(0^-)$, for a single-particle state of good parity. The expectation values of the matrix elements of the single-particle parity operator for orbitals near the Fermi level of ^{151}Pm as functions of octupole deformation β_3 are displayed in Fig. 4. While the core parity splitting energy in octupole transitional nuclei of the actinide region is approximately equal to 400 keV, the observed value is around 750 keV for even-even nuclei in the Ba/Sm region [18]. Assuming this large value, we cannot reproduce the observed value of parity splitting in the proposed ground-state PD's with

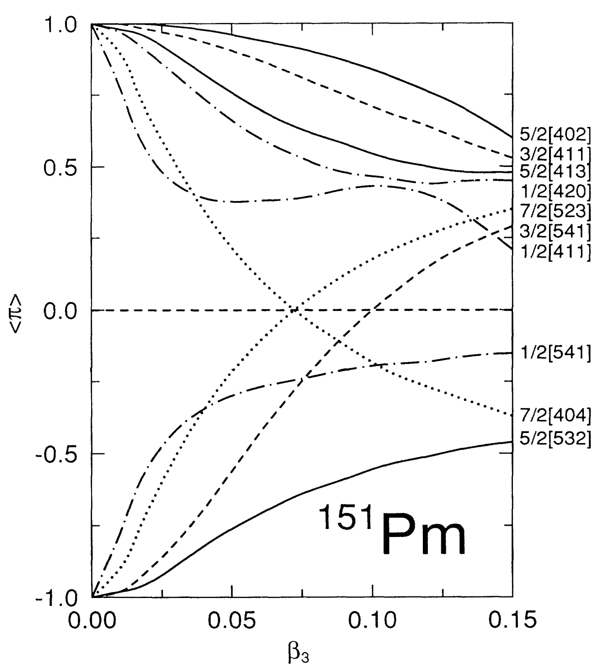

FIG. 4. The expectation value of the matrix elements of the single-particle parity operator $\langle\pi\rangle$ for orbitals near the Fermi level of ^{151}Pm, drawn as functions of octupole deformation β_3 . Solid lines are used for orbitals with $\Omega = 5/2$, dashed lines for $\Omega = 3/2$, dotted lines for $\Omega = 7/2$, and dot-dashed lines for $\Omega = 1/2$. Asymptotic quantum numbers, relevant at $\beta_3 = 0$, are given to the right in the figure.

$\Omega = 5/2$ $[E(I^-) - E(I^+) \approx 100$ keV], since all proton orbitals with Ω=5/2 have $|\langle\pi\rangle| > 0.45$. That is also true for the odd-proton ^{153,155}Eu nuclei.

VI. CONCLUSIONS

As a result of this investigation we can conclude that low-spin features, such as the magnetic moments of low-lying states and decoupling parameters of the $K = 1/2$ rotational bands of odd-proton nuclei ^{151}Pm, ^{153,155}Eu and odd-neutron nuclei ^{153}Sm, ^{155}Gd, previously suggested as octupole deformed, can be explained without introducing the idea of static intrinsic reflection asymmetry in essentially all cases. This result agrees with calculations of polarization energies of octupole-driving orbitals, since there are not any octupole-driving orbitals for which the polarization energy is sufficient for stabilization of octupole deformed shapes. In a similar way, the calculation of polarization energies of unpaired nucleons in two-quasiparticle states of odd-odd ^{152,154,156}Eu nuclei do not support the existence of SIRA shapes for experimentally observed states.

In this description, the small energy splitting between the levels of different bands with equal K but opposite parity has then to be explained as an accidental near degeneracy of the two Nilsson orbitals. The enhanced $E1$ ($\Delta K = 0$) transitions between the levels of ground-state bands and their counterparts with equal K can be understood, for example, within the quasiparticle-phonon nuclear model and nonadiabatic rotational model treatment of Ref. [29] in terms of added contributions from the even-even core. These calculations show that this model can explain enhanced $E1$ transitions in the odd-proton nuclei ^{153,155}Eu using a reflection symmetric mean field.

Another interesting feature that is outside the scope of the present investigation is the inversion of odd-even staggering of nuclear charge radii. Such inversion is seen in the Eu isotopic chain with A = 152–155 [8,22,30]. There is some experimental evidence that such inversion takes place exactly in those nuclei for which reflection asymmetric shapes were theoretically predicted and supported also by spectroscopy results in Ra/Th and Ba/Sm regions [31]. However, it is not clear at present if this phenomenon can be taken as direct evidence for SIRA or can be explained without invoking the SIRA idea.

Taking into account all features discussed above, we believe that static intrinsic reflection asymmetry at low spin does not exist in the $Z \sim 62$ and $N \sim 90$ rare-earth region. On the other hand, we have not considered the possibility of dynamic intrinsic reflection asymmetry which according to Refs. [20,32,33] is an important feature of these nuclei.

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