High-spin parity doublets in the nucleus 151 Pm

Urban, W; Bacelar, JC; Gast, W; Hebbinghaus, G; Krämer-Flecken, A; Lieder, RM; Morek, T; Rząca-Urban, T

Published in:
Physics Letters B

DOI:
10.1016/0370-2693(90)90889-E

High-spin parity doublets in the nucleus ^{151}Pm

W. Urban, J.C. Bacelar
Kernfysisch Versneller Instituut, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

W. Gast, G. Hebbinghaus, A. Krämer-Flecken, R.M. Lieder
Forschungszentrum Jülich, D-5170 Jülich, FRG

T. Morek and T. Rząca-Urban
Institute of Experimental Physics, Warsaw University, ul. Hoża 69, PL-00-681 Warsaw, Poland

Received 21 May 1990

The high-spin-level structure of the nucleus ^{151}Pm has been investigated by in-beam γ-ray spectroscopy using the ^{150}Nd(α, p2N)^{151}Pm reaction. The observed enhanced E1 transitions with B(E1) of the order of 10^{-3} W.u. and parity doubling, both features characteristic of a reflection-asymmetric mean field, suggest an octupole deformation in $^{151}_{61}$Pm.

Since the first detailed considerations of octupole deformation in the odd-mass actinide nuclei [1] rich experimental information has been obtained in favour of this phenomenon. An analogous prediction of breaking of reflection symmetry in the neutron-rich nuclei in the $56 \leqslant Z \leqslant 62$, $86 \leqslant N \leqslant 90$ region [2] is also well supported by experiment but unlike in the actinides here the main experimental effort has been devoted to study even–even nuclei (see ref. [3] and references therein). Moreover, except for the ^{146}Ba case, this information was limited to $N \leqslant 88$ since the rather sudden increase of the quadrupole deformation at $N=89$ prevents the occurrence of $s=+1$ alternating parity bands in even–even nuclei with $N \geqslant 90$. At $N=90$ one can expect the maximum effect since the Fermi level lies between the $\Delta j=3$, $f_{7/2}$ and $i_{13/2}$ neutron orbitals. Recently, it has been recognized that the existing information on the low-spin levels in odd-A and odd–odd nuclei from this region suggests octupole deformation in the $89 \leqslant N \leqslant 91$ isotones [4]. The primary evidence for the reflection asymmetry in the odd-A nuclei is the appearence of parity doublets connected by enhanced E1 transitions. As noticed in ref. [4] a number of pairs of low-lying levels with the same K quantum number and opposite parity, observed in odd-Z nuclei around $N=90$, can be interpreted as parity doublets due to their small energy splitting and enhanced E1 transitions between them. It is interesting to extend the experimental evidence on these nuclei to high spins since in these well-deformed nuclei the low-spin parity doublets should continue as regular alternating-parity bands.

In the present work we report the observation of high-spin parity doublets in the odd-Z nucleus $^{151}_{61}$Pm. The experimental information for ^{151}Pm was re-evaluated recently [5] and has been interpreted in favour of the octupole deformation in this nucleus [6]. In our work we established alternating-parity bands with enhanced E1 transitions which suggest an octupole shape at high spins in ^{151}Pm. This is the first report on the high-spin parity doublets in the lanthanide region.

The experimental data on ^{151}Pm come from the investigation of the ^{150}Nd(α, p2n)^{151}Pm reaction, a by-product of the ^{150}Nd(α, xn)$^{154-x}$Sm study at an α-beam energy of 68 MeV [7]. Measurements have been performed at the JULIC cyclotron of the KFA Julich, where we used the OSIRIS spectrometer to collect γ–γ coincidences. Six Compton-suppressed Ge counters have been arranged in the beam plane, four at 36° and two at 93° with respect to the beam direction. In this way directional-correlation ratios (DCO) could be determined for the observed γ rays. We used the pulsed beam of the cyclotron to measure γ-RF times in the nanosecond range. In the present work we identified 68 γ rays belonging to ^{151}Pm, 16 of which have been reported previously. The assignment to the nucleus ^{151}Pm is based on coincidences with known transitions in this nucleus [5]. Intensities of γ rays have been determined from the coincidence data. For the transitions in ^{151}Pm we have not found any lifetime longer than 5 ns, which was the experimental limit in our experiment. This excludes an M2 assignment to any of the observed transitions. Therefore all transitions with DCO ratios consistent with a $\Delta I=2$ assignment are interpreted as stretched E2. Considering the coincidence relations between observed γ rays we propose a decay scheme of the nucleus ^{151}Pm as shown in fig. 1. Spin and parity assignments to the levels are based on DCO ratios from the present work, the known spins and parities of the band heads [5] and (as mentioned above) E2 assignments for the quadrupole transitions.

The most characteristic feature of the level scheme of ^{151}Pm is the presence of enhanced E1 deexcitations. We identified two cascades of stretched E1 ($\Delta I=1$) transitions which extend up to spins of about $\frac{21}{2}$ and a number of $\Delta I=0$, E1 transitions. In these two alternating-parity bands we also observed crossover transitions of stretched E2 character. In fig. 1 they are arranged in four bands based on top of the $\frac{5}{2}^+$, ground state; the $\frac{7}{2}^+$, 85.1 keV; the $\frac{5}{2}^-$, 116.8 keV and the $\frac{7}{2}^-$, 175.1 keV levels, respectively. In addition we have observed mixed M1/E2 transitions between levels of the same parity. In a previous study, the positive-parity levels were interpreted as a $K=\frac{5}{2}$ rotational band based on a $\pi d_{5/2}\,\frac{5}{2}[413]$ Nilsson orbital. In the same way the negative parity levels were interpreted to have a $\pi h_{11/2}K=\frac{5}{2}$, [532] configuration. However, in the present work, because of the observation of enhanced E1 transitions we propose a simplex classification to the levels in ^{151}Pm. The simplex quantum number gives a good representation of eigenstates in a reflection asymmetric potential [8]. Using the simplex quantum number s, we interpret the two E1 cascades as $s=i$ and $s=-i$ alternating-parity bands, built on top of the $\frac{5}{2}^+$, ground- and the $\frac{5}{2}^-$, 116.8 keV states respectively. We also extend to higher spins the strongly coupled band based on the $\frac{3}{2}^+$, 255.7 keV level reported previously as a $\frac{3}{2}$ [411] configuration [5].

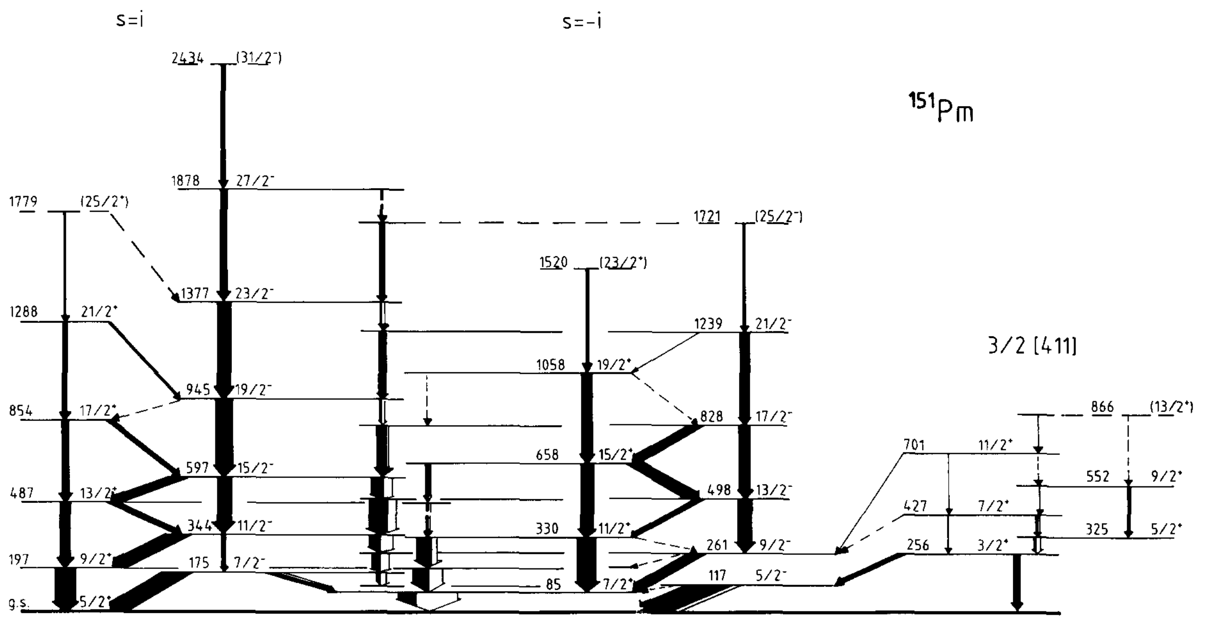

Fig. 1. The decay scheme of ^{151}Pm.

According to the theory [9] the $\frac{5}{2}^+$ and $\frac{5}{2}^-$ band members with $s=i$ and $s=-i$, respectively, should originate from the same intrinsic orbital, which occurs in a reflection-asymmetric potential as a result of the mixing of $\Delta j=3$ orbitals having the same K quantum number (if an axially symmetric potential, which conserves K, is considered). This phenomenon is expected to occur in specific regions of the nuclear chart where $\Delta j=3$ orbitals come close in energy. In the lanthanide region, the relevant orbitals are the $d_{5/2}$ and $h_{11/2}$ for protons and $f_{7/2}$ and $i_{13/2}$ for neutrons. The specific proton orbitals for ^{151}Pm have the $\frac{5}{2}$ [413] and the $\frac{5}{2}$ [532] configurations, respectively. In the case of octupole deformation these two orbitals merge into a single, $K=\frac{5}{2}$ intrinsic orbital of mixed parity. In the laboratory frame one should therefore observe a pair of close lying $\frac{5}{2}^+$ and $\frac{5}{2}^-$ levels, being projections of the intrinsic state on a good parity, which is called a parity doublet. In a well-deformed nucleus, this doublet should continue to high spins since rotational bands of similar properties are built on top of the $\frac{5}{2}^+$ and $\frac{5}{2}^-$ states. The observation of two series of close-lying, opposite-parity levels in ^{151}Pm may be then taken as a hint for octupole deformation in this nucleus. Although the deexciting E2 and E1 transitions clearly suggest the existence of two bands with simplex i and $-i$, the level energies in each simplex are different from the values expected for a rotational simplex band. Similar results were observed in ^{221}Th and ^{223}Th [10].

An important indication for an octupole shape is the presence of enhanced E1 transitions between parity doublets [9]. To estimate the enhancement of the E1 radiation in ^{151}Pm we calculated B(E1) rates using experimental branchings ratios found in the present work, which are shown in fig. 2 and taking B(E2) values from an interpolation of the systematics of the B(E2) rates for even–even nuclei [11]. The validity of this interpolation is justified by a measurement of the B(E2) rates in ^{153}Eu [12]. The resulting B(E1) values are listed in table 1. For the purpose of further discussion we also include in table 1 other B(E1) rates in ^{151}Pm [5]. There are three groups of B(E1) values which differ significantly in magnitude. The B(E1) values corresponding to transitions between parity doublets scatter around 10^{-3} W.u. An average B(E1) value for these transitions is $(1.6+0.3)\times10^{-3}$ W.u., a value comparable to the collective B(E1) rates in

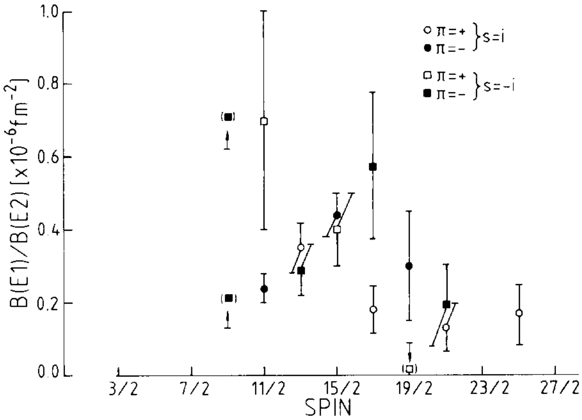

Fig. 2. The B(E1)/B(E2) branching ratios in ^{151}Pm as a function of the spin of the deexciting state. Lower (upper) limits are indicated by arrows up (down).

the actinides. They are about four orders of magnitude faster than those of the group with the lowest values ranging from 10^{-8} to 10^{-6} W.u., which are single particle rates corresponding to transitions between non-parity doublets. The group of middle-range values, which are between 10^{-6} and 10^{-5} W.u., corresponds to transitions between levels belonging to the $\Delta j=3$ pair having however different K values. The above observation of strongly enhanced E1 transitions between parity doublets in ^{151}Pm is a sign for octupole deformation in ^{151}Pm.

The B(E1) rates can be translated into an electric dipole moment Q_1 using the rotational formula

$$B[\mathrm{E1}; KI\to K(I-1)] = 3/4\pi\, Q_1^2 \langle I K 1 0 | (I-1) K\rangle^2 .$$

Taking an average value of $B(\mathrm{E1})=0.003\ e^2\ \mathrm{fm}^2$ for ^{151}Pm and assuming spin $I\sim6$ one obtains a value for the electric dipole moment $Q_1=(0.18+0.03)\ e\,\mathrm{fm}$ which is comparable to values found for the $Z\geqslant60$, $N=88$ lanthanides [3,13].

It is also interesting to look at the proton dependence of the electric dipole moment Q_1, which has been recently discussed for $Z\leqslant62$ [13]. The relevant experimental data are presented in fig. 3. In addition we include in fig. 3 our result for ^{151}Pm as well as Q_1 values which we evaluated from B(E1)/B(E2) data for the following $Z\geqslant62$ isotopes: ^{153}Eu [14], ^{155}Tb

Table 1
The B(E1) rates of transitions in the nucleus ^{151}Pm. Data for the $\frac{3}{2}$ [411] band and for the $\frac{5}{2}$ [402] state are taken from ref. [5].

	Initial level E_{exc} (keV)	I^{π}	E_{γ} (keV)	B(E1) [a] [W.u.]
$s=\pm i$ bands	116.8	$\frac{5}{2}^-$	31.7	$8.4(17)\times10^{-4}$
			116.8	$1.4(2)\times10^{-3}$
	175.1	$\frac{7}{2}^-$	90.0	$>2.0\times10^{-4}$
			175.1	$>1.2\times10^{-4}$
	261.2	$\frac{9}{2}^-$	63.9	$>2.1\times10^{-3}$
			176.1	$>4.4\times10^{-4}$
	329.7	$\frac{11}{2}^+$	68.5	$2.9(13)\times10^{-3}$
	344.0	$\frac{11}{2}^-$	146.4	$5.8(17)\times10^{-4}$
	487.1	$\frac{13}{2}^+$	143.0	$1.8(4)\times10^{-3}$
	497.8	$\frac{13}{2}^-$	168.0	$1.4(4)\times10^{-3}$
	597.3	$\frac{15}{2}^-$	110.2	$2.3(4)\times10^{-3}$
	658.2	$\frac{15}{2}^+$	160.4	$2.1(6)\times10^{-3}$
	827.9	$\frac{17}{2}^-$	169.6	$3.3(12)\times10^{-3}$
	854.2	$\frac{17}{2}^+$	256.9	$1.0(4)\times10^{-3}$
	945.0	$\frac{19}{2}^-$	90.8	$2.0(10)\times10^{-3}$
	1058.0	$\frac{19}{2}^+$	229.8	$<5.3\times10^{-4}$
	1239.4	$\frac{21}{2}^-$	181.6	$1.3(7)\times10^{-3}$
	1287.8	$\frac{21}{2}^+$	342.8	$9.2(40)\times10^{-4}$
$\frac{3}{2}$ [411] band	255.7	$\frac{3}{2}$	138.8	2.7×10^{-5}
	853.0	$\frac{5}{2}$	736.2	$>3.6\times10^{-6}$
$\frac{5}{2}$ [402] state	1297.7	$\frac{5}{2}$	551.1	2.0×10^{-8}
			720.3	1.8×10^{-8}
			765.4	9.7×10^{-8}
			1122.6	7.3×10^{-7}
			1180.9	2.1×10^{-6}

[a] These values are deduced from the measured $B(E1)/B(E2)$ ratios using B(E2) rates of 130 W.u., 190 W.u., 220 W.u., 270 W.u. and 330 W.u. for the first, second, etc., E2 transition in cascade, respectively. The B(E2) values were obtained from interpolation between $B(E2; I\to I-2)$ rates in the ground state bands of ^{150}Nd and ^{152}Sm [11].

[15], ^{148}Sm [7], ^{150}Gd [16] and ^{152}Gd [17]. The observed trend in Q_1 as a function of Z indicates a local enhancement of octupole effects in lanthanide nuclei with a maximum around $Z=60$ protons. The data in fig. 3 also show a systematic trend in Q_1 as a function N suggesting a maximum for the electric dipole moment at $N=88$ neutrons.

In summary, we have observed in the ^{151}Pm nucleus two rotational bands of alternating parity built on top of $\frac{5}{2}^+$, ground- and $\frac{5}{2}^-$, 117 keV levels. The E1 γ rays deexciting levels in these bands have B(E1) rates of the order of 10^{-3} W.u., which is two to four orders of magnitude stronger than other E1 transitions observed in ^{151}Pm. We interpret the two bands as a simplex $s=\pm i$ parity doublet, characteristic of the reflection-asymmetric mean field. The results obtained for ^{151}Pm indicate that the region of possible octupole deformation extends in lanthanides to at least $N=90$ neutrons. The systematics of the Q_1 dipole moments in this region suggest the maximum effect around $Z=60$, $N=88$.

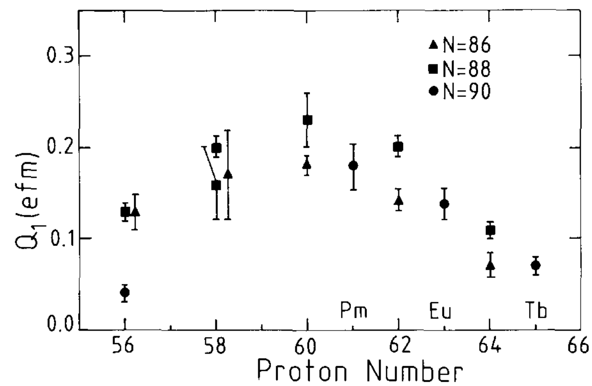

Fig. 3. The experimental values of the dipole moment Q_1 for $86\leq N\leq 90$, $56\leq Z\leq 65$ nuclei.

References

[1] R.R. Chasman et al., Phys. Lett. B 96 (1980) 7.
[2] G.A. Leander et al., Phys. Lett. B 152 (1985) 284.
[3] W.R. Phillips et al., Phys. Lett. B 212 (1988) 402.
[4] R.K. Sheline, Phys. Lett. B 219 (1989) 222.
[5] B. Singh et al., Nucl. Data Sheets 55 (1988) 185.
[6] P.C. Sood and R.K. Sheline, Phys. Rev. C 40 (1989) 1530.
[7] W. Urban et al., Proc. Intern. Conf. on Nuclear structure (Melbourne, Australia, 1987), ed. H. Bolotin, p. 44.
[8] W. Nazarewicz et al., Phys. Rev. Lett. 52 (1984) 1272.
[9] G.A. Leander and R.K. Sheline, Nucl. Phys. A 413 (1984) 375.
[10] M. Dahlinger et al., Nucl. Phys. A 484 (1988) 337.
[11] S. Raman et al., At. Data Nucl. Data Tables 36 (1987) 1, and references therein.
[12] J.E. Thun and T.R. Miller, Nucl. Phys. A 193 (1972) 337.
[13] A.S. Mowbray et al., Nuclear Physics Appendix to the Daresbury Annual Report 1988/89, p. 22.
[14] G.D. Dracoulis et al., J. Phys. G 1 (1975) 853.
[15] G. Winter et al., Nucl. Phys. A 176 (1971) 609.
[16] E. ter Mateosian, Nucl. Data Sheets 48 (1986) 345.
[17] D.R. Zolnowski et al., Phys. Rev. C 21 (1980) 2556.