PHYSICAL REVIEW C, VOLUME 62, 024317

High spin states in singly closed ^{143}Pm

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(Received 17 December 1999; published 20 July 2000)

The high spin states in the $N=82$ odd-A ^{143}Pm have been investigated by in-beam γ-spectroscopic techniques following the reactions ^{135}Ba(^{11}B,3n)^{143}Pm at $E=47$ MeV and ^{133}Cs(^{13}C,3n)^{143}Pm at $E=63$ MeV, respectively, using a gamma detector array, consisting of 12 Compton-supressed high purity germanium detectors and a multiplicity ball of 14 bismuth germanate elements. 28 new γ rays have been assigned to ^{143}Pm on the basis of the γ-ray singles and γ-γ coincidence data. The level scheme of ^{143}Pm has been extended up to an excitation energy of 8.4 MeV and spin $47/2\hbar$ and 24 new levels have been proposed. Spin-parity assignments for most of the newly proposed levels have been made using the measured directional correlation orientation ratios for strong transitions. The observed level structure is discussed in the light of available experimental data and a modest shell model calculation done by us, using the OXBASH code.

PACS number(s): 21.10.−k, 23.20.−g, 27.60.+j, 21.60.Cs

I. INTRODUCTION

In recent years, the odd-A $N=82$ isotones, in between the two double-closed nuclei, ^{132}Sn and ^{146}Gd, have got renewed interest from the standpoint of both theory and experiment [1,2]. From the earlier experimental investigations [3] of the low-lying excitations in these nuclei, it has been seen that these states are mostly pure proton excitations and could be reasonably described by the shell model [4,5] or by using the quasiparticle Tamm-Dancoff approximation [6], assuming ^{132}Sn as a core and distributing the remaining protons outside $Z=50$ core over $1g_{7/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$ orbitals. Some years back, Wildenthal [1] carried out comprehensive shell model calculations for all known $N=82$ nuclei, ranging from ^{133}Sb to ^{154}Hf and found out that by using an uniform orbit space and truncation alogorithm, a vast amount of available data for low spin states could be reasonably described with a constant set of single particle energies and two-body matrix elements. This generated futher interest in the experimental investigations of high spin states, in particular, for nuclei with $Z\leqslant 64$ and A around 140. The high spin structure of such single closed shell nuclei is likely to exhibit a highly irregular level structure, typical of a near spherical nucleus and is expected to be dominated by multiparticle (hole) excitations in which one or more protons are promoted to the empty $1h_{11/2}$ orbital, across the $Z=64$ subshell.

From the available γ-spectroscopic data in this mass region, it is revealed that though there exist some systematic studies for neutron deficient rare-earth nuclei with $Z\leqslant 64$, the data for nuclei near $A=140$ and $N=82$ are rather incomplete because of the use of light ion projectiles, such as proton, deuteron, or alpha particles, in most of the earlier studies. The level structures of the two N = 82 isotones, viz., ^{141}Pr and ^{143}Pm, were studied by Kortelahti *et al.* [7] using in-beam γ-ray and conversion electron spectroscopy following (p,2n) and (d,2n) reactions. These authors proposed several new low- and medium-spin levels up to 3 MeV and spin of $19/2\hbar$. Prade *et al.* [8] studied the high spin states in ^{143}Pm up to 4.58 MeV excitation and spins $25/2^+$ and $23/2^-$, respectively, using ^{141}Pr(α,2n) and ^{143}Nd(d,2n) reactions. The same group [9] also investigated the high spin states in ^{141}Pr using ^{139}La(α,2$n\gamma$) and ^{140}Ce(d,$n\gamma$) reactions up to $E_x\leqslant 4.75$ MeV and spins up to $J=27/2\hbar$. Recently, Piiparinen *et al.* [2] studied the $N=82$ isotone ^{145}Eu up to 11.2 MeV excitation and very high spin ($55/2\hbar$). These authors interpreted the level scheme to be dominated by proton multiquasiparticle states with respect to the doubly magic ^{146}Gd and identified tentatively a set of states above 6 MeV, arising out of neutron excitations across the $N=82$ core. To our knowledge, there exists no such data in the literature for ^{143}Pm and ^{141}Pr using heavy ions. In that context, it would be very interesting to investigate the level structures of the aforesaid nuclei to higher spins and to test the applicability of the extended shell model. It is expected that such studies would allow one to extend the systematics observed in ^{145}Eu to lower odd-A isotones and to look for the probable dilution of the effects of $Z=64$ subshell closure. With this motiva-

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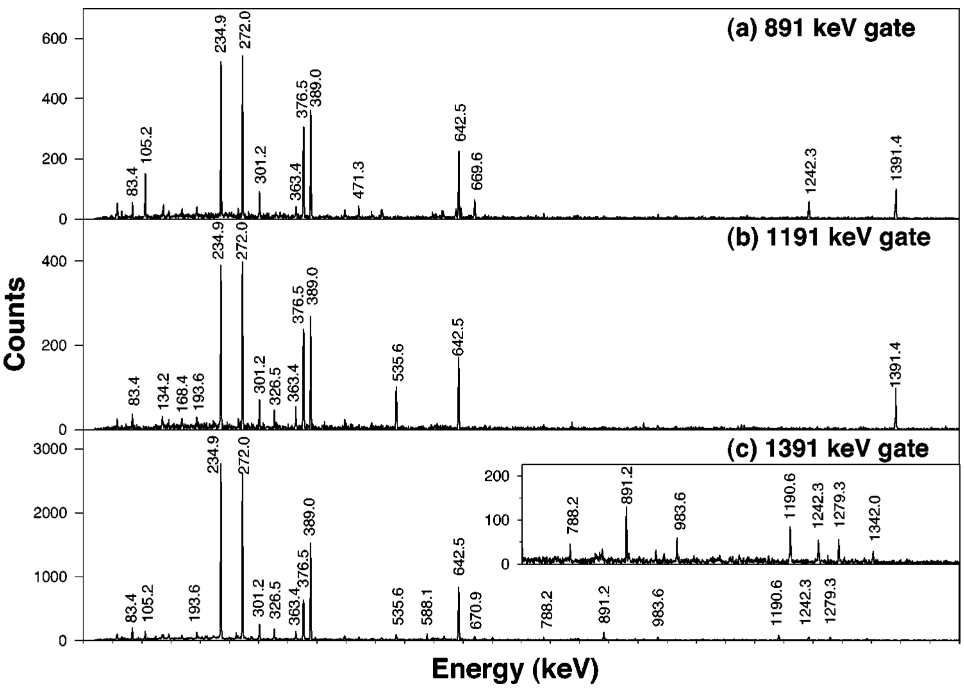

FIG. 1. Representative γ-γ coincidence spectra, observed in the reaction ^{135}Ba(^{11}B,xn) at $E=47$ MeV (reaction I), corresponding to selected gates, as indicated.

tion, we have investigated the high spin level structure of ^{143}Pm using in-beam γ-spectroscopic techniques following (HI,xn) reactions. Some preliminary results of our investigations have been reported elsewhere [10].

Prade *et al.* [8,9], in an attempt to interpret their experimental data for ^{143}Pm and ^{141}Pr, also did shell model calculations, using the prescriptions of Wildenthal [4], in a restricted model space and achieved reasonable agreement for positive parity states though the same for negative parity was very poor. Very recently, Suhonen *et al.* [11] used the microscopic quasiparticle phonon model (MQPM) to study the level structure of odd-Z ($Z=53-62$), $N=82$ isotones and compared their results with the available experimental data as well as with the calculations, done by Heyde and Waroquier [5] in the traditional quasiparticle phonon model. As the latter calculations do not cater to spin regimes above $15/2^{+}$ and $17/2^{-}$, respectively, we have undertaken shell model calculations for both positive and negative parity states using the code, OXBASH [12], in an extended basis with a view to interpret the present results. In Sec. II, the experimental procedures and the results will be presented. The construction of the level scheme will be described in Sec. III. In Sec. IV, the proposed level scheme will be discussed in the light of available experimental data and the present shell model calculations.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The high spin states in ^{143}Pm were studied in the present work using the Gamma Detector Array (GDA) of Nuclear Science Center (NSC), New Delhi, consisting of twelve 23% Compton-suppressed n-type HPGe detectors (CSS) fixed on two horizontal rings at $\pm 25°$ to the median plane and a multiplicity ball of fourteen hexagonal (38 mm$\times$75 mm) BGO detectors, placed above and below the median plane, at a distance of 4 cm from the target covering about 35% of the total solid angle. The CSS's are placed at a distance of 18 cm from the target and are so arranged that those form three groups of four detectors, each at 45°, 99°, and 153°, respectively with respect to the beam direction, covering about 5% of the total solid angle. The on-line data acquisition system was CAMAC based and configured around a Micro-VAX II computer. The list mode data were sorted using the program ''NSCSORT'' [13], developed for the said purpose. A brief description of the array and the associated data acquisition system can be found in Refs. [14,15].

In the present work, the residual nuclei were produced by two reactions, viz., ^{135}Ba(^{11}B,3n) at $E=47$ MeV and ^{133}Cs(^{13}C,3n) at $E=63$ MeV (to be referred to hereafter as reactions I and II, respectively) using dc beams from the 15UD Pelletron Accelerator of NSC. Typical beam currents ($\approx$2 pnA) were used in the respective experiments. The resulting compound nucleus, ^{146}Pm, was the same in both reactions, but was produced with different angular momentum distributions. The ^{135}Ba target ($\approx$830 μg/cm^2) was prepared by vacuum evaporation of enriched (67.5%) ^{135}BaCO$_3$, supplied by Union Carbide Corporation, on a thick ($\approx$10 mg/cm^2) Tantulum backing. The percentage composition of other neighboring isotopes of Ba in the target were as follows: ^{136}Ba (12.4%), ^{137}Ba (5.6%), and ^{138}Ba (13.2%). The ^{133}Cs target ($\approx$3.5 mg/cm^2) was prepared by centrifuge method using specpure (99.999%) ^{133}CsNO$_3$. A 5 mg/cm^2 Au foil was used as backing in this case and the target was covered from top with a 200 μg/cm^2 evaporated Au film.

Around 6.6×10^{7} two and higher fold coincidence events were recorded in list mode. Each coincidence event was tagged by the condition that at least one BGO detector of the multiplicity ball should fire. The pulse height of each detector was gain matched to 0.5 keV/channel and the γ-γ coincidence data were sorted into a 4096$\times$4096 total E_γ-E_γ ma-

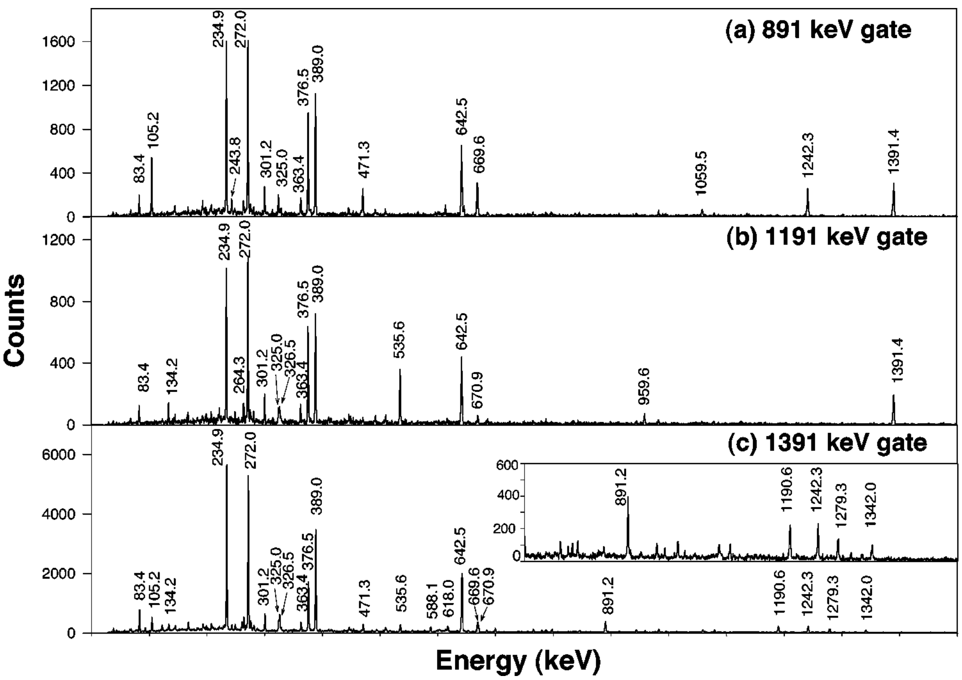

FIG. 2. Representative γ-γ coincidence spectra, observed in the reaction ^{133}Cs(^{13}C,xn) at $E = 63$ MeV (reaction II), corresponding to selected gates, as indicated.

trix from which the energy spectra gated by the γ rays of interest were generated. The γ rays belonging to the various residual nuclei, produced mainly by neutron evaporation from the compound nucleus, were identified by putting gates on known strong transitions, which are already assigned to the respective nuclei from earlier investigations. In case of ^{135}Ba target, the yields of the neighboring contaminant (xn) channels, viz., ^{142,144,145}Pm, were found to be significant because of the presence of other isotopes of ^{135}Ba in the target, as mentioned in the preceding paragraph. In the case of ^{133}Cs target, the γ rays from ^{141,142}Pm and from ^{139}Pr only have been identified, besides ^{143}Pm. The relative yields of the various observed channels have been estimated and are found to be consistent with the calculations for the respective reactions using the PACE2 code [16]. In Figs. 1–4, some representative coincidence spectra from the two reactions, corresponding to some pertinent gates in ^{143}Pm are shown. It is evident from the coincidence spectra, observed in the two reactions (cf. Figs. 1 and 2), against 891.2, 1190.6, and 1391.4 keV gates that additional γ rays have been seen in-reaction II, which have been originated from the deexcitaion of higher lying levels above 4.58 MeV of excitation in ^{143}Pm. As the compound nucleus is produced at higher excitation energy and angular momentum in case of ^{13}C-induced reaction, the population of higher spin states in the residual nuclei is favored. This is amply supported by the presence of additional γ rays in the spectra corresponding to reaction II (as shown in Figs. 2–4), when compared with the same (shown in Fig. 1), observed in reaction I.

The multipolarities of the observed transitions were determined from directional correlation orientation (DCO) ratios, for which two separate 4096×4096 matrices were generated with the events recorded in the 99° detectors along one axis and those recorded in the 45° and 153° detectors respectively along the other axis. Setting gates on known pure quadrupole or dipole transitions, the intensities for other transitions in coincidence were found out and the DCO ratios were determined using the expression [15]

$$R_{DCO}(\gamma_1) = \frac{I(\gamma_1) \;\; \text{at} \;\; 153° \;\; (\text{or} \;\; 45°), \;\; \text{gated by} \, \gamma_2 \;\; \text{at} \;\; 99°}{I(\gamma_1) \;\; \text{at} \;\; 99°, \;\; \text{gated by} \;\; \gamma_2 \;\; \text{at} \;\; 153° \;\; (\text{or} \;\; 45°)} \tag{1}$$

that follows from the prescriptions of Krämer-Flecken *et al.* [17]. For some weak transitions from higher spin states, the ratios were found by adding gated spectra of same multipolarity in the cascade which were cross-checked against both a pure known dipole or quadrupole transition.

III. LEVEL SCHEME OF ^{143}Pm

The level scheme of ^{143}Pm has been extended in the present work up to 8.4 MeV excitation and spin $47/2\hbar$ on the basis of the intensity balance, observed coincidence relation-

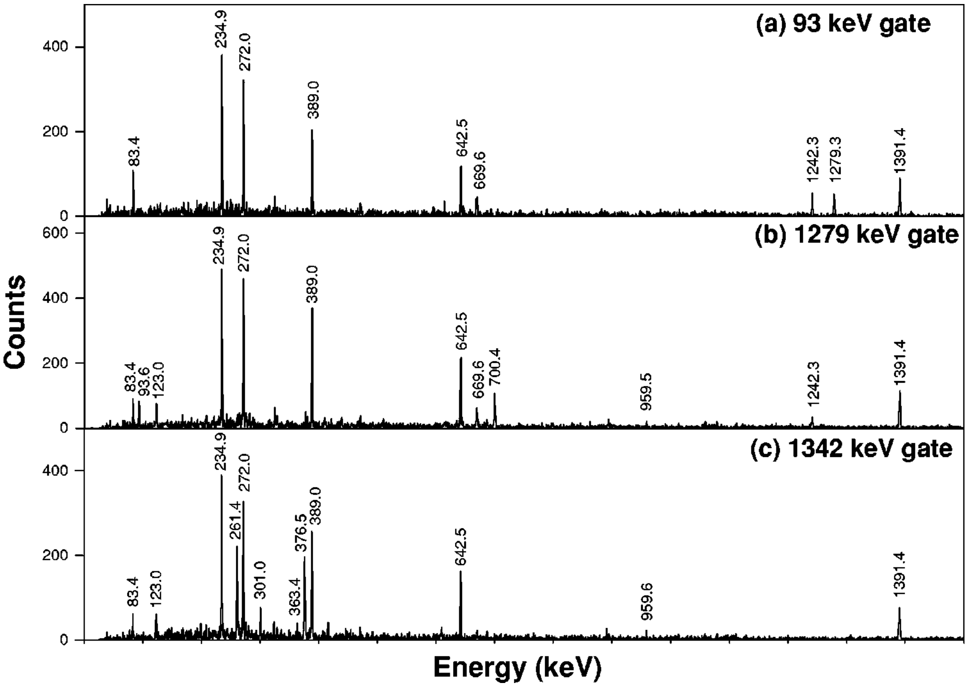

FIG. 3. Representative γ-γ coincidence spectra from reaction II, corresponding to selected gates, as indicated.

ships and the measured DCO ratios from the present work, together with the available information on conversion coefficients, deduced multipolarities and other electromagnetic properties from earlier works [7,8,18,19]. The proposed level scheme, as shown in Fig. 5, is well corroborated by the same obtained from the earlier studies with light ions [7,8,19]. In reaction I, excited states up to 6.3 MeV were populated which have been confirmed from the results, obtained in reaction II. A total of 28 new transitions has been confirmed besides those seen in the earlier study by Prade *et al.* [8] using (α, $2n\gamma$) reaction of which 22 could be placed in the proposed level scheme. Some of the new transitions were also seen by the earlier workers, who, however, did not include those in their level scheme properly. The energies and relative intensities of the observed γ rays in reaction II, together with the measured DCO ratios and other relevant information concerning their placement in the proposed level scheme are given in Table I. Because of the presence of overlapping γ-rays from the competing channels in the total projection spectrum, the relative intensities in some cases were either obtained from the analysis of the appropriate gated spectra or checked for consistency from the gated

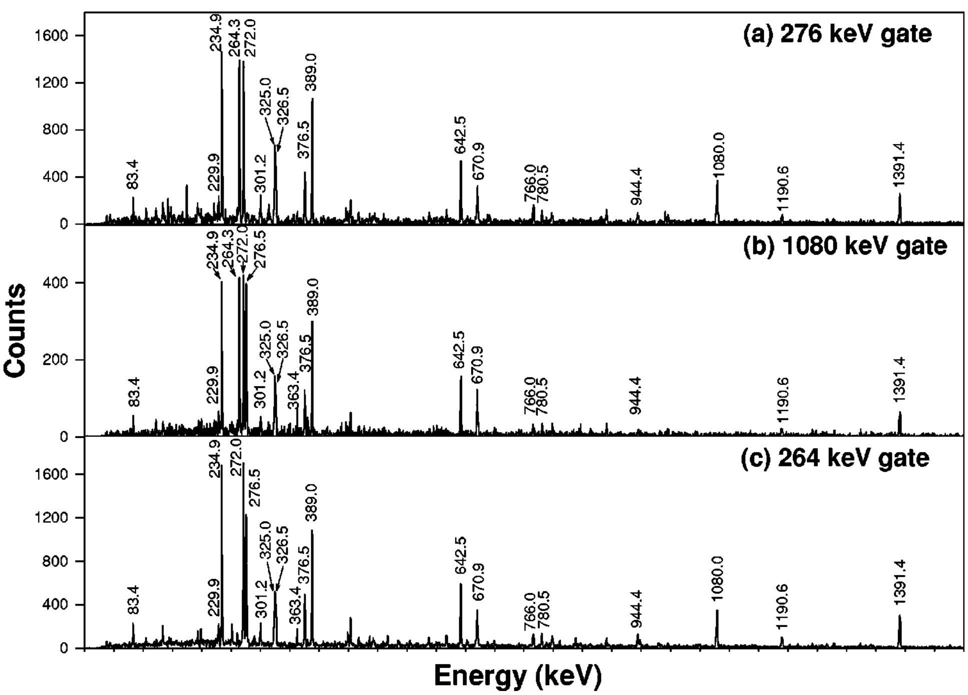

FIG. 4. Representative γ-γ coincidence spectra from reaction II, corresponding to selected gates, as indicated.

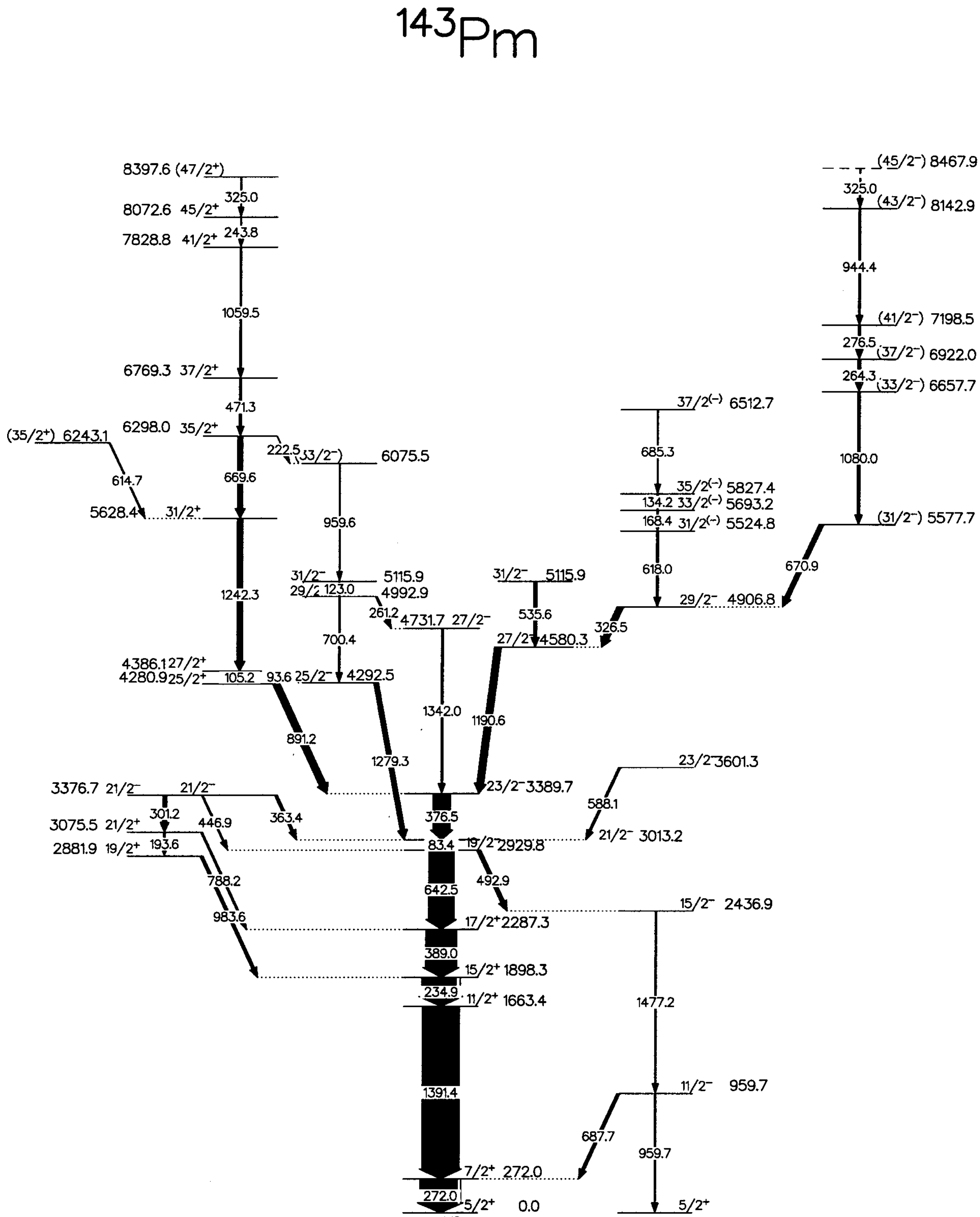

FIG. 5. Level scheme of ^{143}Pm, as proposed in the present work.

spectra of specific transitions. For levels deexcited by multiple transitions, the multipolarities of crossover and cascade γ rays were used to cross-check the spin-parity assignments.

A. Low spin excitations

The present results corroborate well the earlier published data, as compiled in the latest Nuclear Data Sheets (NDS) [19], for low lying levels up to 4.58 MeV. It is observed that the major decay of the population of ^{143}Pm residual nucleus follows through the 376.5–83.4–642.5–389.0–234.9–1391.4–272.0 keV cascade of γ rays. Prade *et al.* [8] measured the conversion coefficients, angular distribution and linear polarization of most of these transitions except for 83.4 keV to fix up their multipolarities. Their conversion

TABLE I. Prompt γ rays in ^{143}Pm from the ^{133}Cs(^{13}C,3n) reaction at $E=63$ MeV.

E_γ[a] (keV)	I_γ[b]	DCO ratio (R_{DCO})	DCO gate Energy (keV)	DCO gate Multipolarity	Deduced Multipolarity	E_i	E_f	J_i^π	J_f^π
83.4	105.4	1.95 ± 0.11	234.9	Q	$M1$	3013.2	2929.8	$21/2^-$	$19/2^-$
93.6	12.1	0.99 ± 0.34	642.5	D	$E1$	4386.1	4292.5	$27/2^+$	$25/2^-$
105.2	53.7	1.58 ± 0.11	234.9	Q	$M1+E2$	4386.1	4280.9	$27/2^+$	$25/2^+$
123.0	25.3	1.37 ± 0.20	234.9	Q	$M1+E2$	5115.9	4992.9	$31/2^-$	$29/2^-$
134.2	27.6	1.55 ± 0.23	1190.6	Q	$M1+E2$	5827.4	5693.2	$35/2^{(-)}$	$33/2^{(-)}$
168.4	36.0	1.67 ± 0.22	234.9	Q	$M1+E2$	5693.2	5524.8	$33/2^{(-)}$	$31/2^{(-)}$
193.6	38.2	1.62 ± 0.29	234.9	Q	$M1+E2$	3075.5	2881.9	$21/2^+$	$19/2^+$
222.5	9.7					6298.0	6075.5	$35/2^+$	$(33/2^-)$
229.9[c]	15.8								
234.9	929.4	0.99 ± 0.20	1391.4	Q	$E2$[d]	1898.3	1663.4	$15/2^+$	$11/2^+$
243.8	26.9	0.96 ± 0.20	1242.3	Q	$E2$	8072.6	7828.8	$45/2^+$	$41/2^+$
261.2	44.0	1.48 ± 0.13	234.9	Q	$M1+E2$	4992.9	4731.7	$29/2^-$	$27/2^-$
264.3	74.6	1.04 ± 0.07	234.9	Q	$E2$	6922.0	6657.7	$(37/2^-)$	$(33/2^-)$
272.0	1000.0	1.12 ± 0.02	234.9	Q	$M1+E2$[d]	272.0	0.0	$7/2^+$	$5/2^+$
276.5	56.8	1.14 ± 0.13	234.9	Q	$E2$	7198.5	6922.0	$(41/2^-)$	$(37/2^-)$
301.2	105.4	1.17 ± 0.08	234.9	Q	$M1+E2$[d]	3376.7	3075.5	$21/2^-$	$21/2^+$
325.0[e]	89.5	1.24 ± 0.11	234.9	Q	$M1+E2$	8397.6	8072.6	$(47/2^+)$	$45/2^+$
326.5	160.6	1.23 ± 0.07	1190.6	Q	$M1+E2$	4906.8	4580.3	$29/2^-$	$27/2^-$
363.4	70.5	0.77 ± 0.09	234.9	Q	$M1+E2$[d]	3376.7	3013.2	$21/2^-$	$21/2^-$
376.5	440.6	0.89 ± 0.04	642.5	D	$M1+E2$	3389.7	3013.2	$23/2^-$	$21/2^-$
389.0	806.2	0.94 ± 0.03	642.5	D	$M1$[d]	2287.3	1898.3	$17/2^+$	$15/2^+$
446.9	38.3	0.99 ± 0.17	389.0	D	$M1$	3376.7	2929.8	$21/2^-$	$19/2^-$
471.3	57.2	1.51 ± 0.27	1242.3	Q	$M1+E2$	6769.3	6298.0	$37/2^+$	$35/2^+$
492.9	32.5				$E2$[d]	2929.8	2436.9	$19/2^-$	$15/2^-$
535.6	83.6	0.87 ± 0.14	1190.6	Q	$E2$	5115.9	4580.3	$31/2^-$	$27/2^-$
588.1	54.4	0.99 ± 0.12	389.0	D	$M1$	3601.3	3013.2	$23/2^-$	$21/2^-$
614.7	31.7	0.81 ± 0.28	1242.3	Q	$(E2)$	6243.1	5628.4	$(35/2^+)$	$31/2^+$
618.0	55.7	2.00 ± 0.29	1190.6	Q	$M1/E1$[f]	5524.8	4906.8	$31/2^{(-)}$	$29/2^-$
642.5	682.4	1.02 ± 0.03	389.0	Q	$E1$[d]	2929.8	2287.3	$19/2^-$	$17/2^+$
669.6	140.5	0.59 ± 0.08	891.2	D	$E2$	6298.0	5628.4	$35/2^+$	$31/2^+$
670.9	120.0	0.93 ± 0.22	1190.6	Q	$(M1+E2)$	5577.7	4906.8	$(31/2^-)$	$29/2^-$
685.3	25.8				$(M1+E2)$	6512.7	5827.4	$37/2^{(-)}$	$35/2^{(-)}$
687.7	75.0				$M2$	959.7	272.0	$11/2^-$	$7/2^+$
700.4	40.0	1.01 ± 0.18	234.9	Q	$E2$	4992.9	4292.5	$29/2^-$	$25/2^-$
766.0[c]	43.8								
780.5[c]	14.3								
788.2	46.4	1.13 ± 0.26	234.9	Q	$E2$	3075.5	2287.3	$21/2^+$	$17/2^+$
891.2	186.1	1.08 ± 0.13	642.5	D	$E1$	4280.9	3389.7	$25/2^+$	$23/2^-$
944.4	49.1				$M1+E2$	8142.9	7198.5	$(43/2^-)$	$(41/2^-)$
959.6[g]	67.6				$M1+E2$	6075.5	5115.9	$(33/2^-)$	$31/2^-$
983.6	75.8	1.12 ± 0.16	234.9	Q	$E2$	2881.9	1898.3	$19/2^+$	$15/2^+$
1059.5	40.4	0.93 ± 0.27	234.9	Q	$E2$	7828.8	6769.3	$41/2^+$	$37/2^+$
1080.0	69.8				$M1+E2$	6657.7	5577.7	$(33/2^-)$	$(31/2^-)$
1113.2[c]	23.7								
1190.6	186.3	0.95 ± 0.09	234.9	Q	$E2$	4580.3	3389.7	$27/2^-$	$23/2^-$
1242.3	154.1	0.98 ± 0.09	234.9	Q	$E2$	5628.4	4386.1	$31/2^+$	$27/2^+$
1279.3	126.7	0.48 ± 0.11	642.5	D	$E2$	4292.5	3013.2	$25/2^-$	$21/2^-$
1303.5[c]	28.4								
1324.5[c]	24.4								
1342.0	50.9	0.89 ± 0.14	234.9	Q	$E2$	4731.7	3389.7	$27/2^-$	$23/2^-$
1391.4	1082.0	1.02 ± 0.02	234.9	Q	$E2$[d]	1663.4	272.0	$11/2^+$	$7/2^+$
1477.2	32.5				$E2$[d]	2436.9	959.7	$15/2^-$	$11/2^-$

[a]Typical uncertainty in energy is $\pm(0.1-0.2)$ keV.

[b]Relative γ-ray intensities normalized to the 272.0 keV transition as 1000; overall uncertainty due to peak fitting and efficiency calibration is estimated to be 10% for strong transitions and 15–20% for weak transitions.

[c]Transitions have not been placed in the proposed level scheme.

[d]Adopted from NDS [19].

[e]Placed also between 8467.9 keV and 8142.9 keV state; deduced DCO ratio is uncertain due to double placement.

[f]M1 assignment adopted.

[g]Additional placement; placed also between 959.7 keV state and ground state, following NDS [19].

data agrees well within errors with those of Nagai *et al.* [18]. We have adopted from NDS [19] the assignment of $E2$ multipolarity for the 234.9 keV and 1391.4 keV, $M1$ assignment for the 389.0 keV and $E1$ assignment for 642.5 keV γ rays. These assignments along with the mixed nature of 272.0 keV γ ray could be confirmed by the measured DCO ratios from the present work, which upholds the J^{π} assignments of $5/2^+$, $7/2^+$, $11/2^+$, $15/2^+$, $17/2^+$, and $19/2^-$ for the ground state and the excited states at 272.0, 1663.4, 1898.3, 2287.3, and 2929.8 keV, respectively. Prade *et al.* [8] placed an 83.4 keV transition above 2929.8 keV level and suggested an $M1$ assignment through an estimate of the total conversion coefficient for 83.4 keV γ ray. Within the estimated uncertainty in our measured DCO ratio for 83.4 keV transition, against 642.5 keV ($E1$) gate, our observation supports a pure dipole assignment. This assignment is also corroborated by the DCO ratio, obtained against 1391.4 keV ($E2$) gate, thereby restricting the spin parity for 3013.2 keV level to $21/2^-$. The same authors [8] placed the 376.5 keV transition at two places in their level scheme, one between 3389.7 and 3013.2 keV levels and the other between 2436.9 and 2060.2 keV levels which links to the yrast sequence at 1663.4 keV ($11/2^+$) level by a 396.8 keV transition. From our coincidence data, it is observed that the major intensity of the 376.5 keV γ ray comes from the deexcitation of 3389.7 keV level to 3013.2 keV ($21/2^-$) level within the uncertainty of the intensity measurements. Also, we have not observed the 396.8 keV γ ray, as mentioned above, in the 376.5 keV gate. Hence, a second placement of 376.5 keV, as suggested by Prade *et al.* [8], does not seem to be necessary and the levels at 2060.2 and 2436.9 keV, as proposed by the former workers, are not included in our level scheme. From similar considerations, the level at 3061.0 keV, as proposed by the same workers, on the basis of a weak 1000.8 keV transition, has been excluded from the present scheme. Prade *et al.* [8] could not make unambiguous assignment of the multipolarity of 376.5 keV transition from their angular distribution and polarization data and adopted a spin-parity of $21/2^-$ for the 3389.7 keV level. We have, however, assigned a spin-parity of $23/2^-$ to the 3389.7 keV level, based on $M1+E2$ assignment for 376.5 keV γ ray from our deduced DCO ratio from both reaction I and II. Kortelahti *et al.* [7] proposed a level at 1566.0 keV with $J^{\pi}=(9/2^+)$ on the basis of two transitions at 1566.0 and 1293.9 keV. Though we have seen a weak 1566.0 keV γ ray in the singles spectrum, the presence of a 1293.9 keV γ ray, in coincidence with 272.0 keV, has not been confirmed. The other low spin levels, between 272.0 and 1663.4 keV levels, as suggested by Kortelahti *et al.* [7], are also not included in our level scheme, as the transitions were neither observed in the singles spectrum nor in the coincidence spectrum corresponding to 272.0 keV gate. However, their existence in the level scheme cannot be ruled out as the low spin states are relatively weakly populated in our work due to the use of heavy ion projectiles. The placement of other weak transitions below 3.5 MeV, by Prade *et al.* [8] and adopted in NDS [19], has been confirmed in our work from the coincidence spectra of related gates. The corresponding levels at 959.7 ($11/2^-$), 2436.9 ($15/2^-$), 2881.9 ($19/2^+$), 3075.5 ($21/2^+$), and 3376.7 ($21/2^-$) keV have been retained in the present level scheme.

B. High spin states

As mentioned earlier, most of the new transitions are found to be in coincidence with either 891.2 or 1190.6 keV γ ray (cf. Figs. 1 and 2), depopulating the 4280.9 and 4580.3 keV levels, respectively. Some are also seen in 1279.3 and 1342.0 keV gates (cf. Fig. 3), which are placed above 3013.2 ($21/2^-$) and 3389.7 ($23/2^-$) keV levels from coincidence relationships and intensity balance considerations. This indicates that the high spin structure in ^{143}Pm would develop into different branches, on top of the main yrast sequence ending at 3013.2 keV level. The spin-parities of the levels at 4280.9 and 4580.3 keV were adopted to be ($23/2^+$) and ($25/2^-$), respectively, in the latest compilation of Nuclear Data Sheets [19]. We are, however, in favor of ($25/2^+$) and ($27/2^-$) assignment, consequent to the revised spin-parity of ($23/2^-$) for the 3389.7 keV level. This assignment is in conformity with the $E1$ and $E2$ assignments for 891.2 and 1190.6 keV transitions, respectively, as suggested in Ref. [8] and is supported by our DCO data. In the present work, a new set of levels above 4280.9 keV has been proposed on the basis of the observed coincidences with 891.2 and 1279.3 keV gates. The 105.2 keV transition, placed immediately above 891.2 keV γ ray, was included by Prade *et al.* [8] in their scheme with a tentative spin assignment of (19/2,21/2) for the 4385.9 keV level on the basis of excitation function data. Though a dipole assignment was suggested for this γ-ray by them, our DCO ratio data favor an $M1+E2$ assignment and hence a spin-parity of $27/2^+$ has been proposed for the 4386.1 keV level. A relatively weak 93.6 keV transition connects this level to a new level at 4292.5 keV, which is deexcited to the 3013.2 keV ($21/2^-$) level by a 1279.3 keV transition. This placement is corroborated by the observation of a 93.6 keV γ ray in the spectra, gated by 1242.3 keV and 1279.3 keV γ rays and its absence in 891.2 keV gate (cf. Fig. 3). The $E2$ multipolarity of 1279.3 keV γ ray, as deduced from DCO data, favors a spin-parity of $25/2^-$ for the 4292.5 keV level. This restricts the multipolarity of the 93.6 keV γ ray to be $E1$, which is supported by the DCO ratio, deduced from 642.5 keV gate.

The level scheme, above the 4386.1 keV level, is constructed with the help of several new transitions found in coincidence with the 891.2 keV γ ray in reaction II. Out of the newly reported transitions in this branch, the 1242.3 keV γ ray is the strongest one, placed above 4386.1 keV level and is assigned to be of pure $E2$ multipolarity from our DCO data. Hence, the corresponding level at 5628.4 keV is assigned a spin-parity of $31/2^+$. A close doublet with energies of 669.6 and 670.9 keV has been clearly identified in ^{143}Pm from our work. Though the said γ rays are not well resolved in the total projection spectrum, one could conclude from the gated spectra corresponding to 891.2 and 1190.6 keV transitions respectively that those are actually two close lines. Prade *et al.* [8] observed a weak transition at 671.9 keV, which they have placed tentatively between the 3601.5 keV (23/2) and the 2929.8 keV ($19/2^-$) levels in parallel to the

588.1 keV dipole transition, depopulating the former level. However, the observation of 670.9 keV γ ray in the 376.5 keV and 1190.6 keV gates rules out the above tentative placement of 671.9 keV γ ray, by the previous workers [8]. A detailed analysis of this doublet has been done by channel by channel projection from the γ-γ coincidence matrix which confirmed their placement in two different branches above the 891.2 and 1190.6 keV transitions. From the DCO ratios corresponding to the 891.2 keV and 1242.3 keV gate transitions, which are of $M1$ and $E2$ multipolarity, respectively, it is concluded that the 669.6 keV γ ray is of $E2$ multipolarity. Hence, the level at 6298.0 keV, proposed for this transition, is assigned a spin-parity of $35/2^+$. The 670.9 keV γ ray is placed in another branch tentatively above the 326.5 keV γ ray on the basis of intensity balance. The deduced DCO ratio for this transition against 1190.6 keV gate suggests a mixed multipolarity and a tentative assignement of $(31/2^-)$ for the 5577.7 keV level. A multiplet at 325 keV is observed in the total projection spectrum, which is contaminated by γ rays belonging to ^{142}Pm [15]. The other members of the 325 keV multiplet could be very clearly resolved and seen in the gated spectra, corresponding to 891.2 (or 1242.3) and 1190.6 keV, respectively. We have preferred to place 325.0 keV γ ray at two places in the level scheme, as discussed later in this section and the 326.5 keV γ ray has been placed above the 1190.6 keV transition. The transitions at 471.3, 1059.5, and 243.8 keV have been placed in the 891.2 keV branch above 6298.0 keV level from coincidence considerations and the corresponding new levels at 6769.3, 7828.8, and 8072.6 keV are assigned spin-parity of $37/2^+$, $41/2^+$, and $45/2^+$, respectively, from the deduced multipolarity. A 614.7 keV γ ray is seen in coincidence with 1242.3 keV but not with 669.6 keV and is placed between the 6243.1 and the 5628.4 keV levels with a tentative spin-parity of $(35/2^+)$ for the former level. The 325.0 keV transition which is most probably of mixed multipolarity, has been placed above 8072.6 keV from observed coincidence relationship and intensity balance in the 891.2 keV gated spectrum. The corresponding level at 8397.6 keV is assigned a tentative spin-parity of $(47/2^+)$. A 326.6 keV transition has been known to occur in the neighboring nuclei ^{144}Pm [20] which was produced in reaction I due to contamination in enriched ^{135}Ba; but the other strong coincidence γ rays belonging to ^{144}Pm could not be seen either in 326.5 or in 1190.6 keV gated spectra in reaction II. So the 326.5 keV transition, seen in coincidence with 1190.6 keV γ ray, in reaction II, arises mainly from the ^{143}Pm nucleus and is placed between 4906.8 and 4580.3 keV levels. The levels at 4731.7, 4992.9, and 5115.9 keV are proposed on the basis of the coincidences observed with the γ rays in the main yrast sequence as well as with the 1190.6, 1342.0, and 1279.3 keV γ rays, respectively. The good agreement in energy sums of the corresponding cascade transitions, viz., 1279.3–700.4–123.0, 1342.0–261.2–123.0, and 1190.6–535.6 keV establishes well the said levels beyond doubt. Of these, the levels at 4731.7 and 5115.9 keV level are assigned spin parities of $27/2^-$ and $31/2^-$ respectively on the basis of deduced $E2$ multipolarity for the 1342.0 and 535.6 keV γ ray, which is seen well in coincidence with all the γ rays in the main yrast sequence. This fixes the spin parity of 4992.9 keV level to be $29/2^-$. The intensity of the 959.6 keV γ ray, seen in the coincidence spectra against 1190.6, 1342.0, and 1279.3 keV gates, necessitates another placement of this γ ray above 5115.9 keV level though an $E3$ transition of same energy has been placed by the earlier workers [8], between 959.7 keV $(11/2^-)$ and the $5/2^+$ ground state. Therefore, a new level at 6075.5 keV is proposed with tentaive spin parity of $(33/2^-)$, which is connected to the 6298.0 keV level by a weak 222.5 keV transition. The 618.0 keV γ ray, placed above 326.5 keV transition, is likely to be a dipole transition ($E1$ or $M1$) from DCO ratio data and we have adopted an $M1$ multipolarity and a tentative spin parity of $31/2^{(-)}$ for the 5524.8 keV level. The 134.2 keV transition was also observed and placed previously by Prade *et al.* [8]; but they had placed it above the 3389.7 keV level in parallel to 1190.6 keV transition. However, in the present work, we have seen a reasonable coincidence between 134.2 and 1190.6 keV γ rays and also with all other γ rays, viz., 168.4 and 685.3 keV, placed in the same sequence. The placement of the above γ rays was fixed above the 5524.8 keV level on the basis of intensity balance of the transitions corresponding to 1190.6 keV gate. Prade *et al.* [8] could not do any multipolarity assignment for 134.2 keV transition because of the likely contamination from ^{144}Pm nucleus. However, in our experiment with reaction II, there was no possibility of contamination from ^{144}Pm. The measured DCO ratios are in favor of a mixed multipolarity for the 134.2, 168.4, and 685.3 keV γ rays. Hence tentative J^π assignments of $33/2^{(-)}$, $35/2^{(-)}$, and $37/2^{(-)}$ has been suggested for 5693.2, 5827.4, and 6512.7 keV levels, respectively.

A set of new transitions with energies of 1080.0, 264.3, 276.5, and 944.4 keV have been identified to belong to ^{143}Pm nucleus, all of which are in coincidence with the transitions below the 3389.7 keV level. These γ rays have been placed above 5577.7 keV $(31/2^-)$ level on the basis of coincidence data and four new levels are tentatively proposed at 6657.7, 6922.0, 7198.5, and 8142.9 keV, respectively. Because of the low yield of these γ rays, only tentative multipole assignment is possible for 264.3 and 276.5 keV transitions and therefore, the spin-parity assignments indicated in the level scheme are very tentative. From the coincidence spectra, corresponding to 264.3, 276.5, and 1080.0 keV gates (cf. Fig. 4), it appears that these are in coincidence with the 325.0 kev γ ray, placed earlier from 8397.6 keV level on the basis of observed coincidences with 891.2, 1242.3, and other γ rays, placed in that cascade. However, we have not observed transition(s), linking the 1080.0–264.3–276.5 keV cascade to the said level. It is possible that there exists an isomer around 8072.6 keV level, similar to the ones observed recently in the neighboring $N=82$ isotones, ^{145}Eu and ^{144}Sm [2] around the same excitation energy and spin regime. However, the present experiment was not aimed to look for such high spin isomers with expected halflife $\leqslant 1$ ns, for which a separate experiment using pulsed beam has been planned. Therefore, a second tentative placement of 325.0 keV γ ray is adopted for the present above 8142.9 keV $(43/2^-)$ level, besides the one mentioned earlier in the positive parity sequence above 8072.6 keV $(45/2^+)$ level.

IV. DISCUSSION

The nucleus ^{143}Pm has three protons less than the doubly-closed ^{146}Gd. As expected, it is spherical in the ground state [21] and the low-lying states are dominated by proton excitations corresponding to $1g_{7/2}$, $2d_{5/2}$, and $1h_{11/2}$ orbitals, as demonstrated by Wildenthal [4,22], in the framework of conventional shell model. Raman *et al.* [23] suggested the existence of neutron particle-hole states in the neighboring ^{142}Nd isotone around 3.5 MeV, whereas the more recent work of Wirowski *et al.* [24] proposes such states with broken neutron-core configurations to occur at around 6 MeV excitation. Hence, one may expect excitations of proton particle (holes) across $Z=64$ subshell, rather than neutron excitations across $N=82$ core to be responsible for the generation of angular momentum in ^{143}Pm at excitation energies below 6 MeV. As mentioned in the Introduction, the shell model calculations of Prade *et al.* [8,9] in a restricted model space were reasonably successful in describing the positive parity states in ^{141}Pr and ^{143}Pm, though the calculated negative parity states were in poor agreement with the available experimental data. Especially, the gap between the $(11/2^-)_1$ level and other higher odd-parity states were calculated to be large. Apart from the neglect of $2d_{3/2}$ and $3s_{1/2}$ orbitals, the noninclusion of $(1h_{11/2})^3$ configurations is considered to be the reason for the poor agreement [9]. The same workers [8] also employed cluster-vibration model (CVM) with three-hole clusters in $Z=64$, $N=82$ core with limited success for positive parity states. However, the negative parity states could be understood better in a particle-core coupling prescription.

In the present work, we have used the code OXBASH and attempted to extend the shell model calculations in a larger basis space than the earlier workers [8,9]. Wildenthal [22] suggested that the most desirable expansion of the basis space would be to include two-proton excitations to $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ orbitals, which the earlier workers could not include due to computational limitations. We have, therefore, included all the five orbitals in the $N=50$–82 proton subshell space, viz., $\pi 1g_{7/2}$, $\pi 2d_{5/2}$, $\pi 2d_{3/2}$, $\pi 3s_{1/2}$, and $\pi 1h_{11/2}$, in our calculations and restricted the minimum and maximum number of particles in each of the orbitals, assuming ^{132}Sn as core. The restrictions in the number of particles in each orbit were decided by the available proton transfer reaction data [3] and is consistent with the predicted orbit occupation numbers, given by Wildenthal [1]. The 11 protons outside ^{132}Sn core were distributed over the nearly degenerate $1g_{7/2}$ and $2d_{5/2}$ orbitals for positive parity states $[(1g_{7/2},2d_{5/2})^{Z-50}]$. Besides, all one-proton excitations, such as, $[(1g_{7/2},2d_{5/2})^{Z-51}$, $(3s_{1/2},2d_{3/2})^1]$ and two-proton excitations, such as $[(1g_{7/2},2d_{5/2})^{Z-52},(3s_{1/2},2d_{3/2},1h_{11/2})^2]$, have been considered. For negative parity states, the considered configurations have been $[(1g_{7/2},2d_{5/2})^{Z-51}$, $(1h_{11/2})^1]$, $[(1g_{7/2},2d_{5/2})^{Z-52},(3s_{1/2}2d_{3/2})^1,(1h_{11/2})^1]$, $[(1g_{7/2},2d_{5/2})^{Z-53},(3s_{1/2},2d_{3/2})^2,(1h_{11/2})^1]$, and $[(1g_{7/2},2d_{5/2})^{Z-53},(1h_{11/2})^3]$. The single particle energies (SPEs) and the various two-body matrix elements (TBMEs) provided in the code under the N82K interaction [12] have been used. The same were obtained from a best fit of the experimental ground state binding energies as well as a large number of excited states with known J^π in several $N=82$ nuclei between $A=136$–145 [25]. We have also used the more refined sets of SPEs and TBMEs, reported recently by Wildenthal and also Blomqvist [1] in order to check the effects of these modified sets of TBME in the level spectra of ^{143}Pm. The details of those observations is being planned for a separate publication [26]. It may be remarked that for a given optimum restriction in the minimum and maximum number of particles in a particular orbital in the $N=50$–82 subshell, the three sets of SPEs and TBMEs used by us give similar root mean squared deviation between the experimental and the calculated energy level spectra. In that respect, the calculations using the so-called, N82K interaction, presently integrated with the OXBASH code, offers reasonable fit to the observed energy spectra for both parities and would be discussed here. The SPEs used and TBMEs were obtained from a global fit of a modest set of spectroscopic data from ^{133}Sb to ^{146}Gd. It is observed that the inclusion of two-proton excitations to $1h_{11/2}$ orbit gives a better fit of the observed higher spin positive parity level structure, though the two proton excitations to $2d_{3/2}$ and $3s_{1/2}$ is no less important. Similarly, it is necessary to include three proton excitations to $1h_{11/2}$ in order to explain the higher spin negative parity states.

In Figs. 6 and 7, respectively, we have compared the proposed high spin level structure of ^{143}Pm with the same obtained from the present shell model calculations. For brevity, we have included only the positive parity states above $25/2^+$ and negative parity states above $23/2^-$ which are newly proposed from the present work. As far as the low spin positive parity states are concerned, the calculation predicts the $7/2^+$ first excited state little lower in energy and the sequence of levels up to $17/2^+$ is under predicted. The higher spin states above $19/2^+$ are better reproduced compared to the ones below; but these are predicted on the higher side. For the former states, the effects of ^{142}Nd core-coupled single particle configurations may be responsible for lowering of the experimental level energies. Enghardt *et al.* [27] have demonstrated that for negative parity states in ^{140}Ce, the particle-core coupling concept seems to be reasonable. Following their observation, we find good correlation in our case between the ^{142}Nd states, both even- and odd-parity ones, with the corresponding states in ^{143}Pm. For example, the $17/2^+$ state, which is predicted by the present shell model calculation at a lower energy, may have significant contributions from core-coupled configurations, such as 6^+ state of ^{142}Nd, coupled to $\pi d_{5/2}$ orbital and 3^- state of ^{142}Nd, coupled to $\pi h_{11/2}$ orbital, both contributing to the observed $17/2^+$ state, whereas from the present shell model calculations, the dominant configurations for the $17/2^+$ state turns out to be 79% $(\pi g_{7/2}{}^6 \pi d_{5/2}{}^5)$, with the rest distributed between $(\pi g_{7/2}{}^7\, \pi d_{5/2}{}^4)$, $(\pi g_{7/2}{}^5\, \pi d_{5/2}{}^5 \pi s_{1/2}{}^1)$.

For negative parity states, the agreement with the experimental level structure is not so good. It is observed that except for the first $11/2^-$ state, this calculation gives better correspondence with the experimental states than the calculations, done with the parameter set used for positive parity

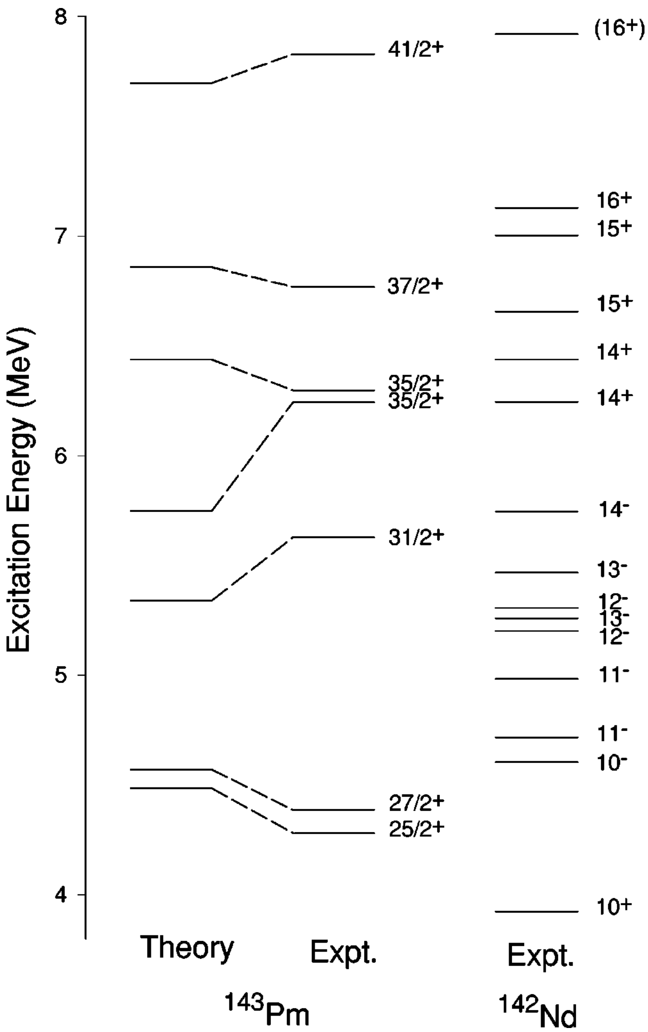

FIG. 6. Comparison of high spin positive-parity level structure of ^{143}Pm, as proposed in the present work, with the same obtained from shell model calculations using OXBASH code. The experimental level structure of ^{142}Nd, around the same excitation energy regime, are also shown to indicate the probable core-coupled states in the observed level spectra of ^{143}Pm (see text).

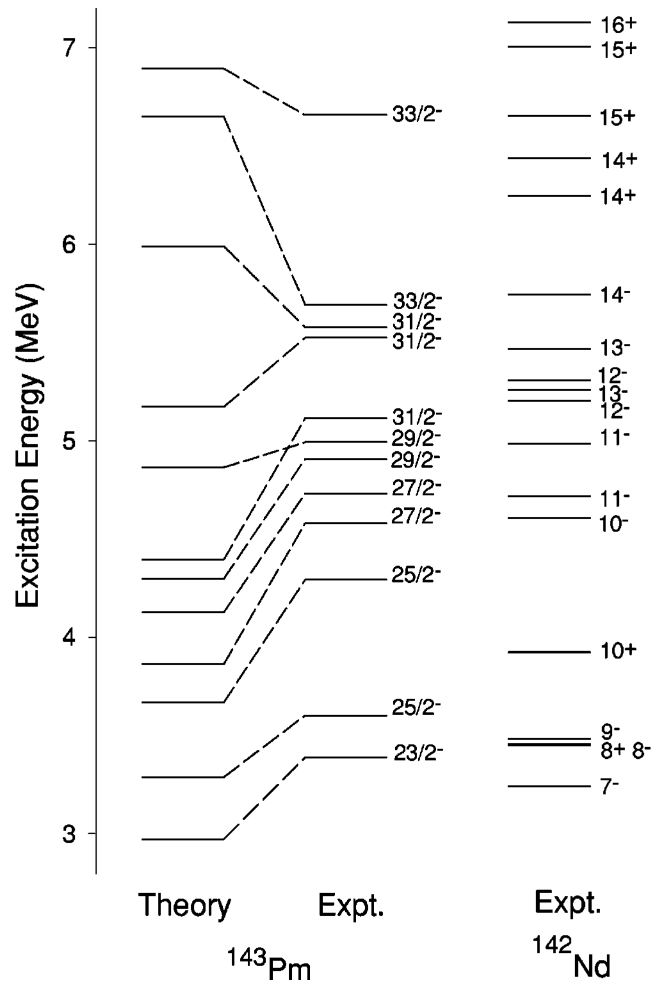

FIG. 7. Comparison of high spin negative-parity level structure of ^{143}Pm, as proposed in the present work, with the same obtained from shell model calculations using OXBASH code. The experimental level structure of ^{142}Nd, around the same excitation energy regime, are also shown to indicate the probable core-coupled states in the observed level spectra of ^{143}Pm (see text).

states. However, the mean absolute deviation between the observed and the theoretical calculations do not differ very much. One could reproduce the first $11/2^-$ state by adjusting the $1h_{11/2}$ single particle energy. However, we have seen that such readjustment affects the positive parity level structure drastically if $(1h_{11/2})^2$ configuration is considered. We have seen that the three-particle excitations to $1h_{11/2}$ orbital, as commented earlier, are very important for the excitation energy regime under consideration. In this case, the core-particle coupling scheme may be more effective because the coupling of the high spin unique parity orbital, such as $\pi h_{11/2}$, may not disturb the ^{142}Nd core states very much, compared to the situation when a proton is added to $1g_{7/2}$ or $2d_{5/2}$ orbitals. This feature is, indeed, substantiated by the observed correlation between the ^{142}Nd and ^{143}Pm negative parity states. It is very likely that the $11/2^-$ (959.7 keV), $15/2^-$ (2436.9 keV) and $19/2^-$ (2929.8 keV) states in ^{143}Pm arise, respectively, from a coupling of $1h_{11/2}$ proton to 0^+, 2^+, and 4^+ states of ^{142}Nd. Similar conclusions have been drawn by Suhonen *et al.* [11] from MQPM calculations and also by Prade *et al.* [8,9] from their CVM calculations. In the same picture, the whole host of negative parity states with $J^\pi = 21/2^-$ to $37/2^-$ may be correlated with the states arising out of coupling either a $2d_{5/2}$ or a $1g_{7/2}$ proton with the 8^- to 14^- states in ^{142}Nd. According to Wirowski *et al.* [24], the above negative parity states of ^{142}Nd have complicated particle-hole structures. The inclusion of such configuration is not possible in the present version of the code OXBASH, used in this work.

V. CONCLUSION

In the present work, we have extended the level structure of ^{143}Pm up to 8.4 MeV excitation and spin $47/2\hbar$, by heavy-ion induced in-beam γ-spectroscopy using an array of twelve Compton-suppressed HPGe γ detectors. Spin-parity assignments for most of the observed new levels have been done. A shell model calculation has been attempted for both positive and negative parity states using the OXBASH code with ^{132}Sn as a doubly closed core with a view to interpret the observed high spin level structure. In absence of experimental data on other electromagnetic properties, the comparison with the calculation is restricted to excitation spectrum only. It is concluded from such comparison that the high spin level structure demands the inclusion of complex multiparticle (hole) excitation in the calculation, which is beyond the scope of the present work.

ACKNOWLEDGMENTS

We would like to thank the staff of NSC Pelletron and VECC target laboratory for their helpful cooperation. Thanks are due to D. C. Epraim of T.I.F.R., Mumbai for his help and suggestions in making the targets. One of us (S.B.) is grateful to B.A.R.C. authorities for kind permission and support to carry out the work. The financial support from the University Grants Commission, Government of India, for S.C. is gratefully acknowledged.

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