Aust. J. Phys., 1974, 27, 869–77

The Decay of ^{147}Nd

C. Rangacharyulu,[A] S. N. Chaturvedi,[B] G. K. Mehta[A] and N. Nath[B]

[A] Physics Department, Indian Institute of Technology, Kanpur-208016, India.
[B] Physics Department, Kurukshetra University, Kurukshetra-132119, Haryana, India.

Abstract

An experimental level scheme has been determined for ^{147}Pm from an investigation of the decay of ^{147}Nd which employed a high resolution Ge(Li) detector and a sum–coincidence spectrometer with fast–slow coincidence. Conclusive evidence is presented for the existence of levels in ^{147}Pm at 182, 228·5, 275, 319·5 and 725 keV besides the six already established levels, while no evidence is found for another six levels suggested by some earlier workers. Thirty-two γ-ray transitions and their cascade relations have been established, and relative intensities have been determined for most of the transitions.

Introduction

The level structure of ^{147}Pm, using a ^{147}Nd source, has been extensively studied by various techniques but considerable disagreement still remains over the number of existing levels of ^{147}Pm and their possible decay modes. Bashandy and El-Haliem (1967) with their iron-free double-focusing spectrometer predicted new levels at 120, 182, 208, 231, 273, 319·5, 398, 552, 724 and 763 keV in ^{147}Pm, in addition to the already established levels at 91, 410, 489, 531 and 686 keV. Hill and Wiedenbeck (1967) established an additional level at 680 keV. Furthermore, the cascade relations in the decay scheme of this nucleus are full of discrepancies.

Promethium-147 is of considerable theoretical interest because of the expected changeover from near-spherical to deformed structure in the vicinity of mass number 147. Hence there is a general need to obtain detailed and precise experimental data in this region. This, together with the existing discrepancies in the earlier investigations, prompted us to carry out an elaborate investigation of the decay of ^{147}Nd. During the course of our work, Fellmann and Patt (1972) published results on the γ-ray spectrum which they obtained with a high resolution Ge(Li) detector. They found that ^{148}Pm impurities in the ^{147}Nd γ-spectrum were mainly responsible for the conflicting observations, particularly in the work of Bashandy and El-Haliem (1967). However, none of the 11 ^{148}Pm impurity peaks indicated by Fellmann and Patt are observed in our ^{147}Nd spectra. Thus our detailed sum–coincidence measurements along with the Ge(Li) γ-spectrum, when corroborated with the Ge(Li)–Ge(Li) fast–slow coincidence studies of Singh and Mehta (1972), yield conclusive information on the complicated level scheme of this nucleus.

Experimental Details

The ^{147}Nd isotope in the form of neodymium chloride of 20 mCi strength was obtained from the Isotope Division of Bhabha Atomic Research Centre (India) by bombarding a spectrometrically-pure enriched target of ^{146}Nd with slow neutrons from a reactor. A thorough check was made for impurities associated with the resulting ^{147}Nd source. For this purpose, two sets of measurements were performed, one using an unpurified source and the other using a radiochemically purified source (radiochemical separation of the isotope was carried out by A. T. Rane at T.I.F.R., Bombay). Both sources were allowed to decay for a week to ensure that the short-lived impurities generated during the bombardment had died out sufficiently. Nevertheless, some long-lived impurities persisted in measurements taken with the unpurified source, although the situation was significantly better with the purified source.

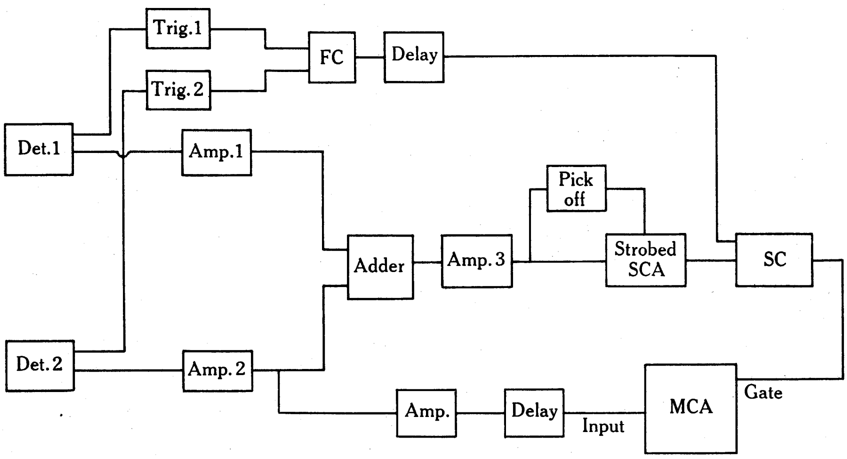


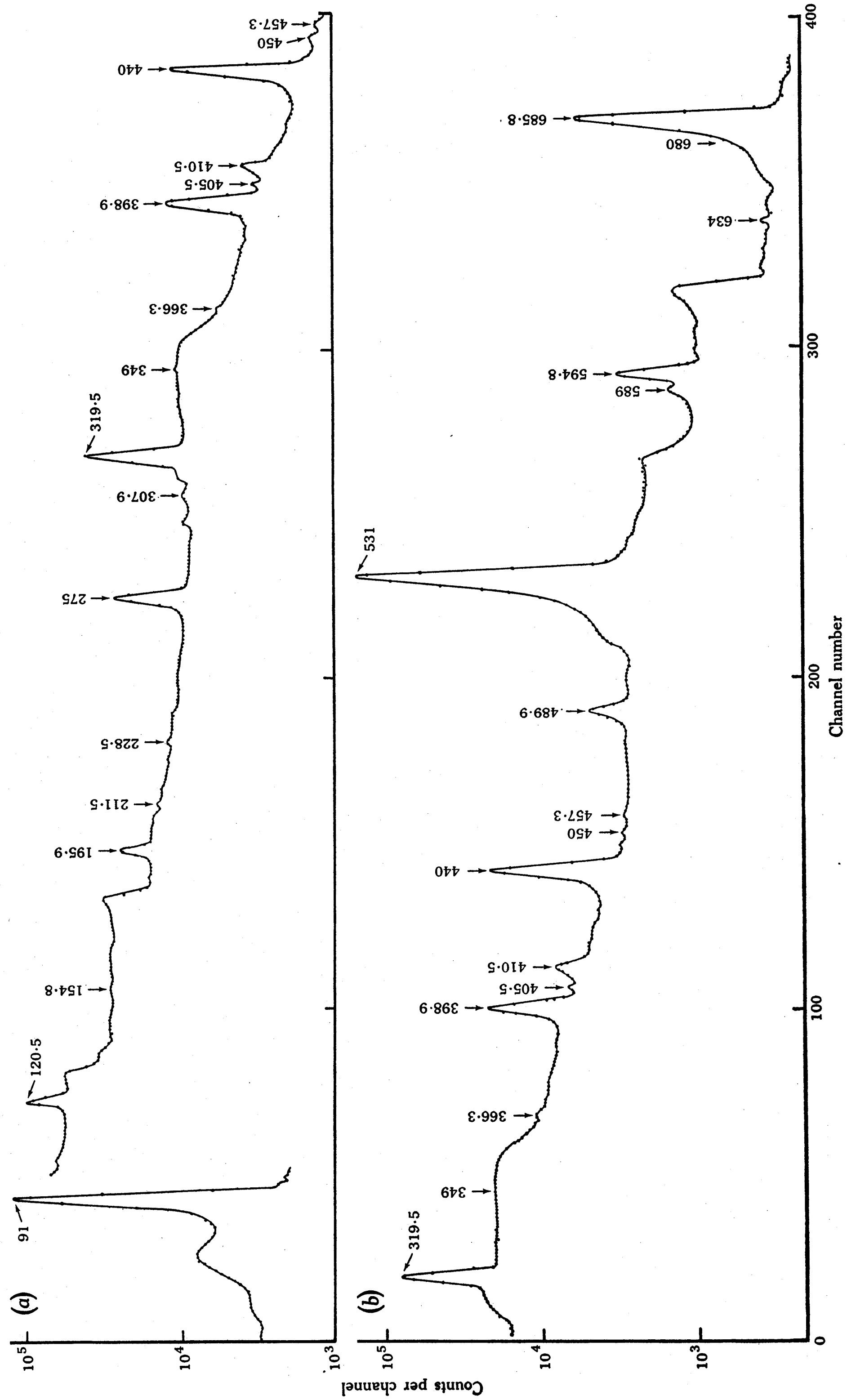
Fig. 1. Block diagram of the sum–coincidence circuitry.

In the present investigation, two types of measurements were carried out. One involved the study of the singles spectra with a Ge(Li) detector of 7 mm depletion depth (4·2 cm^3) and the other involved examination of the sum–coincidence spectra with the fast–slow coincidence technique using two 5 × 5 cm NaI(Tl) detectors. In the singles spectra studies carried out with the Ge(Li) detector, the strength of the source was chosen so as to give about the same dead-time loss in the analyser as was obtained in the case of the standard sources used in the efficiency determination of the same detector. For the sum–coincidence studies the strength of the source was chosen so as to give the best true-to-chance coincidence ratio at the selected resolving time ($\sim$25 ns) of the fast-coincidence circuit.

The Ge(Li) detector was used with an FET preamplifier and possessed a resolution of 3 keV at 662 keV. The efficiency of the detector was determined as a function of energy over the range 80–1332 keV by use of calibrated sources at a fixed source-to-detector geometry (the efficiency curve of the detector was provided by Raghuvir Singh, I.I.T., Kanpur). Corrections were also applied for the absorption of γ-rays in the aluminium window of the detector. Various spectra of ^{147}Nd were recorded at different intervals so as to follow the decay scheme in order to ensure that the spectra were associated with ^{147}Nd and not with an impurity. This procedure also provided better averaged values for the energies of the γ-rays observed. All the data were recorded on a 400-channel analyser. In addition to the spectra taken to cover

---

Fig. 2 (*opposite*). Typical γ-ray singles spectra obtained with the Ge(Li) detector for ^{147}Nd in the energy regions: (*a*) 0–460 and (*b*) 300–700 keV.


Counts per channel
Channel number
(a)
(b)
91
120·5
154·8
195·9
211·5
228·5
275
307·9
319·5
349
366·3
398·9
405·5
410·5
440
450
457·3
489·9
531
589
594·8
634
680
685·8

the entire range of interest, several individual spectra were also taken in stages by expanding a particular energy region using a biased amplifier. This helped to determine the energies and intensities of close-lying γ-rays more precisely than was possible otherwise. To obtain the γ-ray intensities, we had to set a criterion for estimating the 'full energy-peak area'. A statistically flat background which joins the point of maximum radius-of-curvature on the low-energy side to the base of the peak at the high-energy side was adopted. This criterion was also followed to obtain peak areas for the standard γ-rays from calibrated sources used in the efficiency determination of the Ge(Li) detector.

Table 1. Energies and relative intensities of some γ-ray transitions in ^{147}Nd

The energies E_γ are expressed in keV and the intensities I_γ are expressed relative to that of the 531 keV transition

BM*		JHD*		CC*		DE*		Present work	
E_γ	I_γ	E_γ	I_γ	E_γ	I_γ	E_γ	I_γ	E_γ	I_γ
—	—	77·0	5·0	—	—	—	—	—	—
91·0	213	91·1	300	91·0	211	90·9±0·3	248 ±13	91·0±0·4	220 ±14
120·5	3·0	120·5	8	120·6	2·5	120·7±0·3	2·1 ±0·2	120·5±0·4	3·3 ±0·5
—	—	154·0	0·5	—	—	—	—	—	—
196·6	1·5	197·0	2·0	197·0	1·3	196·0±0·6	1·0 ±0·6	195·9±1·0	1·4 ±0·4
275·4	6·4	275·4	7·0	275·1	6·5	275·2±0·5	6·1 ±0·5	275·0±0·6	6·7 ±0·7
319·2	14·5	319·4	15	319·3	14·2	319·5±0·5	15·8 ±1·0	319·5±0·5	16·5 ±1
398·1	6·5	398·0	5·0	397·8	6·4	398·0±0·4	6·7 ±0·5	398·9±0·5	6·5 ±0·7
410·3	1·7	410·0	1·0	409·6	1·3	410·6±0·5	0·9 ±0·2	410·5±0·7	1·2 ±0·3
439·8	8·9	439·8	8·0	439·3	9·2	439·8±0·4	9·7 ±0·6	440·0±0·5	9·8 ±0·2
489·0	1·2	488·4	1·0	488·5	1·5	489·5±0·6	1·2 ±0·3	489·9±0·9	1·4 ±0·4
530·9	100	530·9	100	530·7	100	531·0±0·3	100	531·0±0·5	100
589·0	0·27	—	—	—	—	590·1±1·0	0·26±0·06	589·0±1·6	0·29±0·08
595·5	1·9	593·0	2·0	594·4	2·2	596·2±0·7	1·6 ±0·2	594·8±1·0	2·0 ±0·3
—	—	—	—	—	—	679	0·05	680·0±1·0	0·06
686·3	7·0	685·0	6·0	686·1	6·6	686·3±0·5	5·0 ±0·4	685·8±0·8	6·7 ±0·6

* References to other results are: BM, Backlin and Malmskog (1967); JHD, Jacobs *et al.* (1967); CC, Canty and Connor (1967); DE, Dougan and Erlandsson (1967).

In the sum–coincidence studies, a pair of NaI(Tl) crystals mounted on 56 AVP photomultiplier tubes (10% resolution at 662 keV in singles spectra) were employed as detectors. The two detectors were oriented at an angle of 135° with respect to each other, with lead shielding placed in between. This configuration greatly reduced any crystal-to-crystal scattering which could complicate the interpretation of sum-gated spectra. A schematic diagram of the sum–coincidence circuitry is shown in Fig. 1 which is self explanatory. The arrangement is usual except for the addition of a strobed single-channel analyser and a crossover pick-off unit. This addition compensates the variations in delay with gate settings. To improve the peak resolution for the sum–coincidence spectrum, the sum-gate width was kept as narrow as was consistent with the desired resolution and true-to-chance coincidence ratio in the parallel slow–fast coincidence circuit. To obtain these narrow gate settings, use was made of a biased amplifier (not shown in Fig. 1) which preceded the strobed SCA used for the gating pulse. To accumulate better statistics a wider gate had also to be chosen, but due care was taken to account for peaks arising from other possible interfering cascades satisfying the same sum condition. To avoid gain shift at high counting rates (Gupta and Nath 1967; Chaturvedi and Nath 1972) the photomultiplier dynode chain-circuit was provided with VR tubes across the last two stages. The complete sum–coincidence circuitry was found to be highly stable and could provide consistently reproducible spectra in several independent runs.

Results and Discussion

Ge(Li) Singles Spectra

The entire range of γ-ray spectra has been scanned in three different energy intervals, and typical spectra are shown in Figs 2*a* and 2*b*. Due to low efficiency and the large Compton background, some of the weaker γ-rays could not be located in these spectra, though their presence has been established in the slow–fast sum–coincidence study using the NaI(Tl) detectors. We have calculated the relative intensities of the γ-rays, taking the 531 keV transition as the reference standard. The energies and relative intensities of most of the γ-rays observed by us in the decay of ^{147}Nd are listed in Table 1, where a comparison is also made with earlier results.

Table 2. Summary of sum–coincidence measurements on ^{147}Nd

The observed cascades (labelled *a*, *b*, ... for each sum–coincidence gate energy E_g) are presented in chains of the form:

energy level 1, (γ-ray energy), energy level 2, (γ-ray energy), energy level 3.

All energies are given in keV

E_g		Observed cascade				
182	*a*	182	(91)	91	(91)	0
275	*a*	275	(184)	91	(91)	0
	b	685·8	(154·8)	531	(120·5)	410·5
319·5	*a*	319·5	(137·5)	182	(182)	0
	b	319·5	(91)	228·5	(228·5)	0
410·5	*a*	410·5[A] {	(91)	319·5	(319·5)	0
			(319·5)	91·0	(91·0)	0
	b	725	(194)	531	(211·5)	319·5
	c	685·8	(154·8)	531	(256)	275
489·9	*a*	489·9	(398·9)	91	(91)	0
	b	489·9	(307·9)	182	(182)	0
	c	685·8	(154·8)	531	(349)	182
531	*a*	531	(440)	91	(91)	0
	b	531	(349)	182	(182)	0
	c	531	(256)	275	(275)	0
	d	531	(211·5)	319·5	(319·5)	0
	e	531	(120·5)	410·5	(410·5)	0
594·8	*a*	685·8[A]	(195·9)	489·9	(398·9)	91
	b	685·8	(275·3)	410·5	(319·5)	91
685·8	*a*	685·8	(594·8)	91	(91)	0
	b	680	(589)	91	(91)	0
	c	685·8	(457·3)	228·5	(228·5)	0
	d	685·8	(366·3)	319·5	(319·5)	0
	e	685·8	(275·3)	410·5	(410·5)	0
	f	685·8	(195·9)	489·9	(489·9)	0
	g	685·8	(154·8)	531	(531)	0
725	*a*	725	(634)	91	(91)	0
	b	725	(450)	275	(275)	0
	c	725	(405·5)	319·5	(319·5)	0
	d	725	(194)	531	(531)	0

[A] Either or both of these cascades may occur.

NaI(Tl) Sum–Coincidence Spectra

Sum–coincidence spectra were taken at various gate settings: 182, 275, 319·5, 410·5, 489·9, 531, 594·8, 685·8 and 725 keV. The 39 and 43 keV X-rays from ^{147}Pm are expected to appear in all the sum–coincidence spectra and to add up with some γ-ray component satisfying the sum-gate condition. Obviously, their presence is ignored while assigning observed γ-ray transitions in the decay scheme. Three typical sum–coincidence spectra are shown in Figs 3*a*, 3*b* and 3*c*. In Fig. 3*a* there is no assigned level at the set gate energy, and the spectrum was taken only to examine

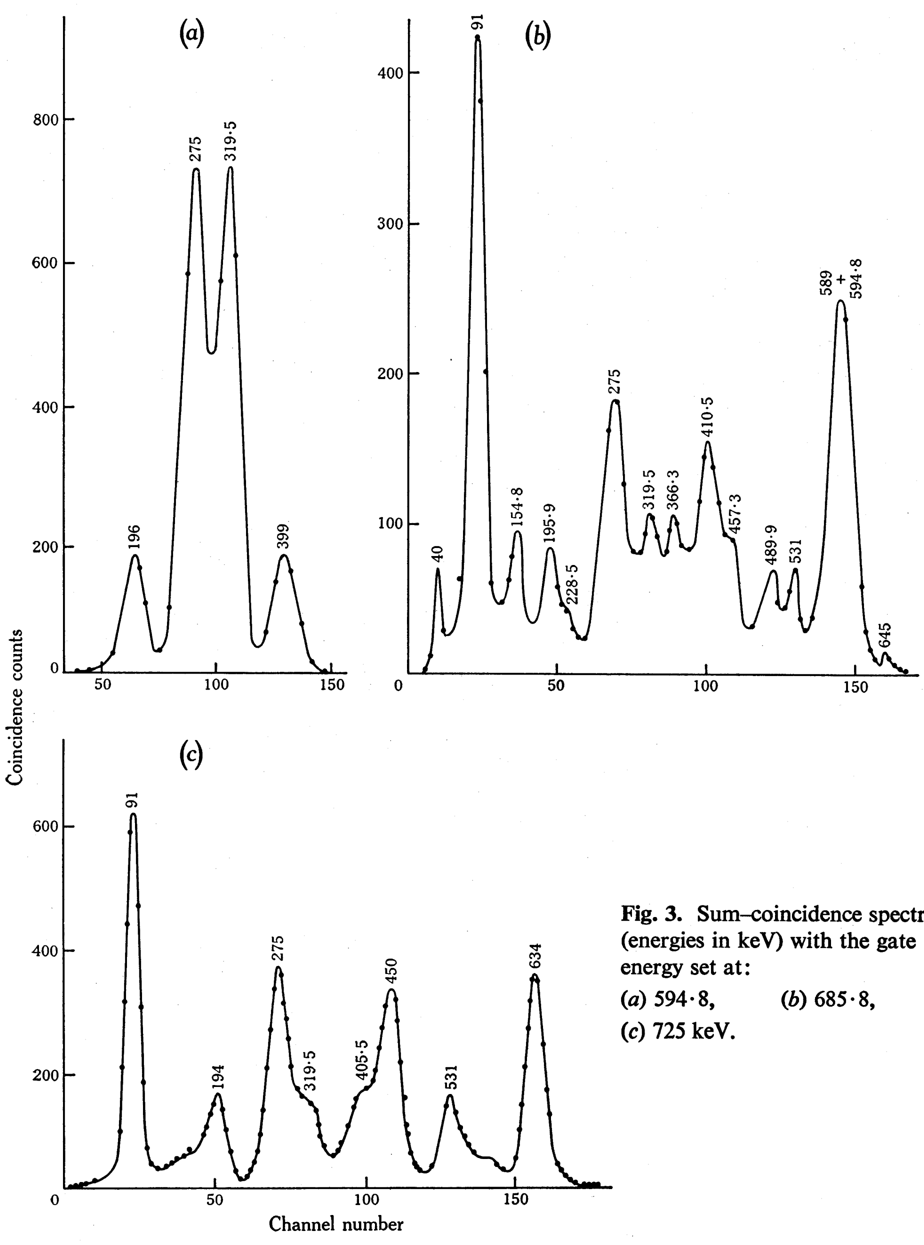


Fig. 3. Sum–coincidence spectra (energies in keV) with the gate energy set at: (*a*) 594·8, (*b*) 685·8, (*c*) 725 keV.

the transitions resulting from the 685·8 → 91 keV decay mode. In Fig. 3*b* the sum gate includes contributions from both the 685·8 and 680 keV levels. In Fig. 3*c* the broadening of the low-energy side of the 194 keV peak and the high-energy side of the 531 keV peak seems to indicate the existence of some new transition However, as this receives no confirmation from other spectra, we explain the broadening as being due to interference between the 685·8 and 680 keV levels in this gate, because in this case a wide gate (± 60 keV) was used to provide better statistics.

The results obtained for the various sum–coincidence spectra are summarized in Table 2. All the γ-rays reported in Table 2 have been well resolved in sum–coincidence studies. However, in the Ge(Li) spectra, the 154·8, 211·5, 228·5, 307·9, 349, 366·3 and 680 keV γ-rays are weakly indicated, while the 137·5, 182, 184, 194 and 256 keV γ-rays could not be seen on account of their low intensity. This reduced sensitivity mainly arises from the limited detection efficiency of our Ge(Li) detector.

Table 3. Summary of evidence for existence of formerly controversial levels

Energy level (keV)	Sum gates providing evidence (keV)	References[A] to earlier reports
182	182, 319·5, 489·9, 531	WD, SLJ, BE, SM
228·5	319·5, 685·8	E, SM
275	275, 410·5, 531, 725	CBHW, BE, SM
319·5	319·5, 531, 685·8, 725	RCB, BE, SM
725	725	SLJ, BE, SM

[A] References: BE, Bashandy and El-Haliem (1967); CBHW, Cork *et al.* (1958); E, Evans (1958); RCB, Rutledge *et al.* (1952); SLJ, Sastry *et al.* (1964); SM, Singh and Mehta (1972); WD, Wendt and Kleinheinz (1960).

Our sum–coincidence study confirms the existence of levels at 182, 228·5, 275, 319·5 and 725 keV in addition to other well-established levels at 91, 410·5, 489·9, 531, 680 and 685·8 keV. The evidence for the existence of these confirmed levels comes from spectra recorded for at least two different sum–coincidence gates, as well as from confirmation supplied by the Ge(Li) singles spectra studies. Table 3 summarizes the evidence we obtained for the presence of these levels from sum-gate spectra studies, together with references to workers who reported their existence earlier.

Evans (1958) suggested a level at 230 keV to accommodate the 230, 260 and 300 keV γ-rays which were originally reported by Rutledge *et al.* (1952). However, we observe a level at 228·5 keV which is populated from the 685·8 and 319·5 keV levels through the 457·3 and 91 keV γ-rays respectively. The 260 and 300 keV γ-rays which were proposed to feed the 230 keV level were not observed by us.

Our detailed sum–coincidence studies confirm the existence of the level at 725 keV. This is in disagreement with the results of a recent investigation by Fellmann and Patt (1972), who examined only Ge(Li) singles spectra and concluded that neither the crossover transition from the 720 keV level nor the 310 keV transition reported by several earlier workers (e.g. Singh *et al.* 1971) in connection with this level exist. Fellmann and Patt attributed these γ-rays to ^{148}Pm impurities, but our Ge(Li) spectra do not show any of the impurity peaks indicated by them. Our sum–coincidence study also supports the cascades from the 725 keV level feeding the 531, 319·5, 275 and 91 keV levels.

Cork *et al.* (1958) proposed a level at 289 keV populated by a 400 keV transition from a 688 keV level and depopulated by a 198·2 keV transition to the 91 keV level. We do not find any indication of this. However, we confirm the findings of Hill and Wiedenbeck (1967) that the 685·8 keV level decays to the 489·9 keV level giving rise to the 195·9 keV transition and that the 489·9 keV level decays to the 91 keV level resulting in the 398·9 keV γ-ray.

The results of our sum–coincidence studies confirm the existence of the 154·8 keV γ-ray reported by Jacobs *et al.* (1967) and Bashandy and El-Haliem (1967). However, we have conclusive evidence that this γ-ray is due to the 685·8 → 531 keV transition (Jacobs *et al.* 1967) and not the 275 → 120 keV transition, as reported by Bashandy and El-Haliem. The 508 keV γ-ray (690 → 182) reported by Sastry *et al.* (1964) has not been observed in the present study. This γ-ray was neither observed in the Ge(Li) singles spectra nor in the 594·8 and 685·8 keV sum-gated spectra.

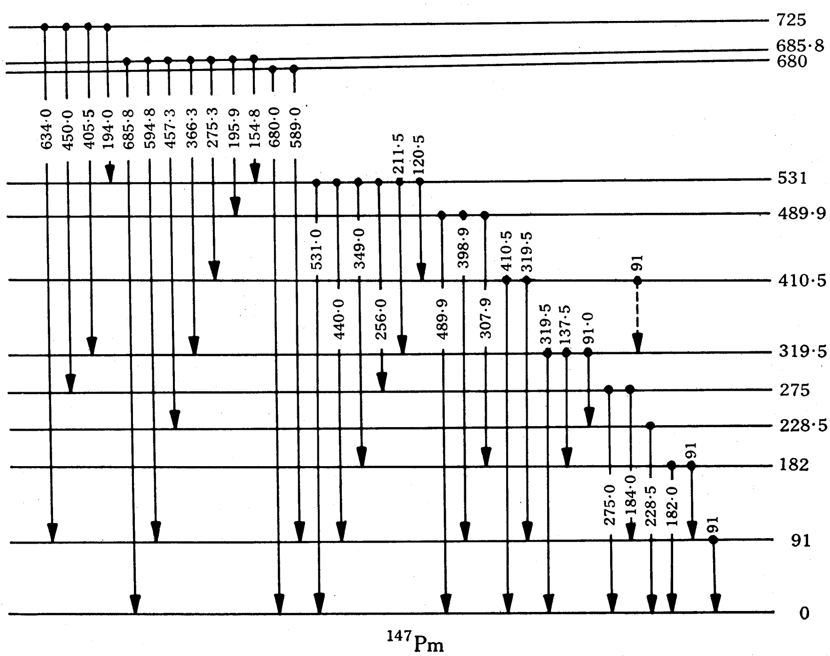


Fig. 4. Proposed level scheme of ^{147}Pm.

The level scheme based on these detailed studies is shown in Fig. 4. The results have shown conclusively that there are no levels in ^{147}Pm at 120·5, 211·5, 398·9, 471, 552 and 763 keV as have been reported by some of the earlier workers. Our level scheme is in agreement with the recently published results of Fellmann and Patt (1972) except for the five levels at 182, 228·5, 275, 319·5 and 725 keV which were not indicated by them. These levels have been established by means of detailed coincidence measurements which they did not undertake. Choudhury and O'Dwyer (1967) have calculated the energy levels of ^{147}Pm, and it is interesting to note that they predict the existence of the same number of levels as observed by us. However, their calculated energies do not agree with the measured ones.

Acknowledgments

Thanks are due to Dr R. M. Singru (I.I.T., Kanpur) for helpful discussions. Two of us (S.N.C. and C.R.) are grateful to the CSIR, India, for fellowships during the course of the investigation. Another two (S.N.C. and N.N.) thank the staff of the Indian Institute of Technology, Kanpur, for extending their facilities to them. One of us (N.N.) wishes to acknowledge the financial support of the Department of Atomic Energy, Government of India, in the form of a research project.

References

Backlin, A., and Malmskog, S. G. (1967). *Ark. Fys.* **34**, 459.
Bashandy, E., and El-Haliem, A. A. (1967). *Z. Naturforsch.* A **22**, 154.
Canty, M. J., and Connor, R. D. (1967). *Nucl. Phys.* A **104**, 35.
Chaturvedi, S. N., and Nath, N. (1972). *Indian J. Pure Appl. Phys.* **10**, 465.
Choudhury, D. C., and O'Dwyer, T. F. (1967). *Nucl. Phys.* A **93**, 300.
Cork, J. M., Brice, M. K., Helmer, R. G., and Woods, R. M. (1958). *Phys. Rev.* **110**, 526.
Dougan, P. W., and Erlandsson, B. (1967). *Z. Phys.* **207**, 105.
Evans, P. R. (1958). *Phil. Mag.* **3**, 1061.
Fellmann, S., and Patt, B. (1972). *Z. Phys.* **257**, 177.
Gupta, A. K., and Nath, N. (1967). *Nucl. Instrum. Methods* **53**, 352.
Hill, J. C., and Wiedenbeck, M. L. (1967). *Nucl. Phys.* A **98**, 599.
Jacobs, E., Heyde, K., Dorikens, M., Demuynck, J., and Dorikens-Vanpraet, L. (1967). *Nucl. Phys.* A **99**, 411.
Rutledge, W. C., Cork, J. M., and Burson, S. B. (1952). *Phys. Rev.* **86**, 775.
Sastry, V. V. G., Lakshminarayana, V., and Jnanananda, S. (1964). *Indian J. Pure Appl. Phys.* **2**, 207.
Singh, R., and Mehta, G. K. (1972). *Indian J. Pure Appl. Phys.* **10**, 733.
Singh, H., Sethi, B., and Mukherjee, S. K. (1971). *Nucl. Phys.* A **174**, 437.
Wendt, H. D., and Kleinheinz, P. (1960). *Nucl. Phys.* **20**, 169.

Manuscript received 14 May 1974