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THE DECAY OF ^{147}Nd

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Abstract: Precision energy measurements on 8 gamma rays in the ^{147}Nd → ^{147}Pm decay were made with a 2m curved-crystal spectrometer. Energies of the 6 other gamma rays were determined with a Ge(Li) spectrometer. The relative intensities of all gamma rays were determined. A level scheme is proposed for ^{147}Pm which includes a new level at 680.4 keV. Evidence is given to support the exclusion of several levels reported by earlier investigators. Results are compared with predictions of intermediate coupling theory.

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RADIOACTIVITY ^{147}Nd [from ^{146}Nd(n, γ)]; measured E_γ, I_γ, $\gamma\gamma$-coin.
^{147}Pm deduced levels, log *ft*. Enriched target.

1. Introduction

The decay of ^{147}Nd to excited states of ^{147}Pm has been studied by many investigators [1-6]). Considerable disagreement exists in regard to number and placement of transitions and arrangement of levels. Previous decay schemes were constructed from gamma spectra obtained by means of NaI detectors. This work was undertaken to construct a more realistic decay scheme using data obtained from a high resolution curved-crystal spectrometer and a lithium-drifted germanium spectrometer. Gamma-gamma coincidences were studied with the aid of the Ge(Li) spectrometer, and upper limits were determined for gamma transitions reported by other investigators.

2. Source preparation

Samples of Nd_2O_3 enriched to 96.2 % in ^{146}Nd were irradiated with thermal neutrons from the University of Michigan Ford Reactor. Flat (ribbon) sources composed of a Nd_2O_3-epoxy mixture were exposed to a flux of 2×10^{13} n/cm^2 · sec for about 25 days. These sources were used in the 2 m curved-crystal spectrometer. Sources for use with the lithium-drifted germanium spectrometer were composed of several mg of Nd_2O_3 dissolved in HNO_3 and irradiated in the Ford Reactor for about 48 hours. After irradiation the rare earths were purified as a group using the procedure of Stevenson and Nervik [7]). No separation of individual rare earths was attempted. The only interfering activities observed were ^{149}Pm ($\tau_{\frac{1}{2}}$ = 53 h) and ^{151}Pm($\tau_{\frac{1}{2}}$ = 28 h) [8]). The presence of these impurities became undetectable a week after irradiation.

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3. Gamma-ray energies

The energies of the eight most intense gamma rays were measured using the 2m curved-crystal spectrometer described by Reidy and Wiedenbeck [9]). All measurements were made using the Ge(400) crystal. This crystal was calibrated using the 411.800 keV transition in ^{198}Au as a standard. The sources were aligned in the spectrometer using the first-order reflection of the 91 keV gamma ray in ^{147}Nd. The resolution widths (fwhm) of the diffraction profiles were approximately 25 sec of arc.

The profile for the 91 keV gamma ray was measured in third order. The 120 and 197 keV gamma-rays were measured in first order, and the 275, 319, 398, 440 and 531 keV gamma rays were measured in second order. The weak gamma rays at 410, 489, 595 and 686 keV were observed but their energies were not measured. It was not possible to observe the weak gamma rays at 589 and 679 keV using the bent crystal spectrometer since their profiles were masked by those of the 595 and 686 keV gamma rays, respectively. During energy measurements the profile of each gamma ray was scanned three times. The energies and errors of the gamma rays measured are listed in table 1. The errors were determined by the method of Reidy and Wiedenbeck [9]).

The gamma-ray spectrum was measured with a lithium-drifted germanium spectrometer having an area of 4 cm^2 and a depletion depth of 0.5 cm. The detector was operated under a reverse bias of 400 V. The resolution width (fwhm) obtained for the 662 keV gamma ray from ^{137}Cs was 3.4 keV. A typical gamma spectrum for ^{147}Nd

TABLE 1

Gamma-ray energies and relative intensities

Energy (keV)	Relative intensity [c])
91.105±0.0016 [a])	227 ±35
120.49 ±0.009 [a])	3.3 ± 0.5
196.66 ±0.03 [a])	1.5 ± 0.6
275.42 ±0.02 [a])	6.8 ± 1.4
319.41 ±0.03 [a])	16.3 ± 2.4
398.22 ±0.07 [a])	6.8 ± 1.1
410.3 ±0.4 [b])	1.2 ± 0.5
439.85 ±0.08 [a])	9.3 ± 1.1
489.3 ±0.35 [b])	1.1 ± 0.5
531.01 ±0.07 [a])	100
589.3 ±0.7 [b])	0.31± 0.14
594.7 ±0.4 [b])	1.9 ± 0.4
679.4 ±1.5 [b])	0.23± 0.16
685.8 ±0.35 [b])	5.9 ± 1.0

[a]) Energy measured using curved-crystal spectrometer.

[b]) Energy measured using Ge(Li) spectrometer.

[c]) Intensities normalized to 100 for the 531.01 keV gamma ray.

is shown in fig. 1. No gamma transitions were observed above 690 keV, and the half-lives of all transitions ascribed to ^{147}Nd were observed to have the correct value of 11.1 d [8]. No effects due to coincidence summing were observed.

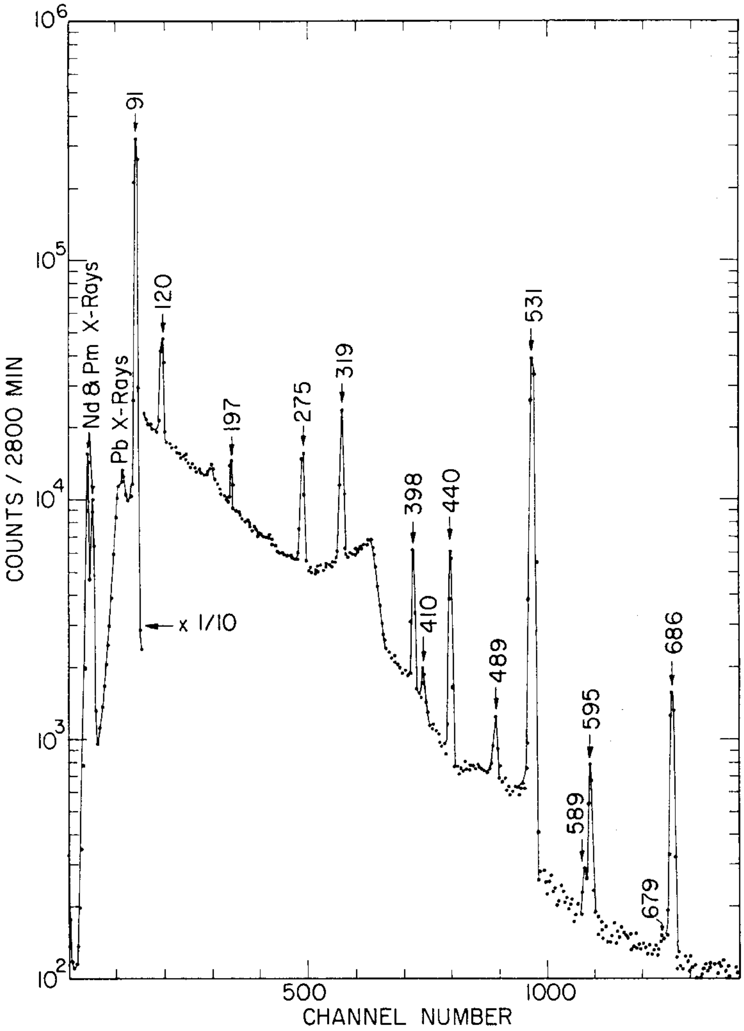

Fig. 1. The pulse-height spectrum of gamma radiation accompanying the decay of ^{147}Nd. The source distance to the 5 mm Ge(Li) spectrometer was 2 cm. No absorber was used. All energies are in keV.

The energies of the six gamma rays at 410, 489, 589, 595, 679 and 686 keV were measured with the Ge(Li) spectrometer. The spectrum was calibrated using the lines in ^{147}Nd at 319, 398, 440 and 531 keV which had been measured accurately using the curved-crystal spectrometer. At higher energies the 661.6 keV gamma-ray in ^{137}Cs was used. The position of each photopeak was determined from the midpoint of the peak at fwhm. The five calibration energies were least squares fitted to a straight line. The minimum error for the determination of energies from this curve was found to be 0.35 keV. Energies and errors of all gamma transitions are given in table 1.

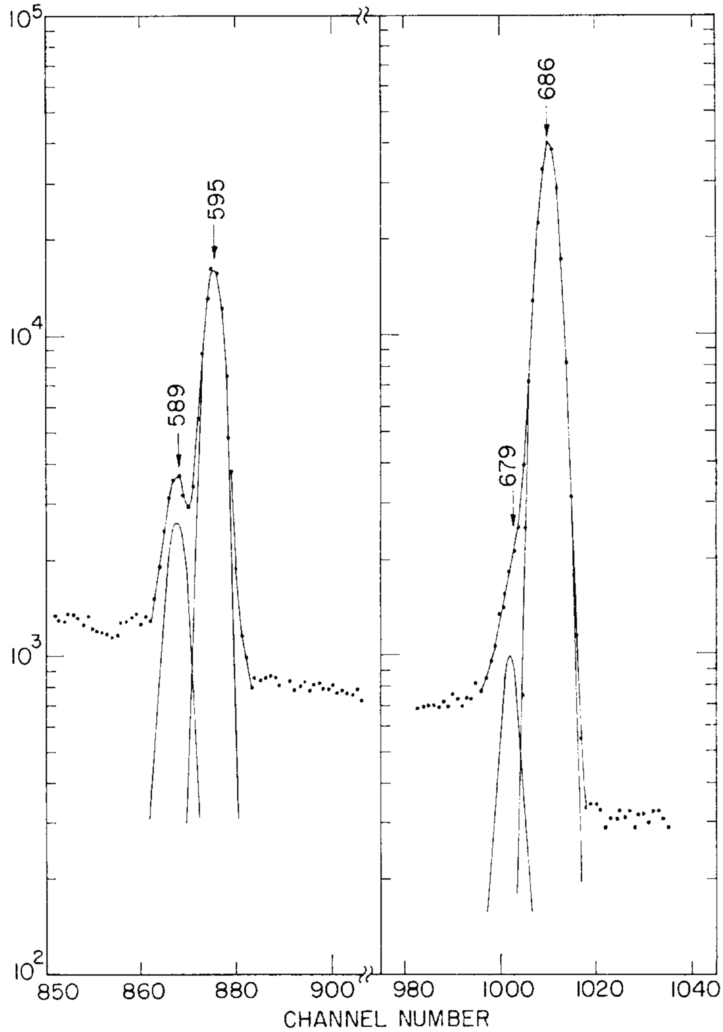

Fig. 2. The pulse-height spectrum of gamma radiation from 575 to 615 keV and from 665 to 700 keV accompanying the decay of ^{147}Nd. The source distance to the 5 mm Ge(Li) spectrometer was 2 cm. An 0.32 cm Pb absorber was used. All energies are in keV.

Two weak gamma rays at 589.3 and 679.4 keV were found superimposed on stronger lines at 594.7 and 685.8 keV, respectively. The corresponding spectra are shown in detail in fig. 2. The energies of these two weak transitions were determined after the stronger component of each doublet had been subtracted. The errors are correspondingly larger.

4. Gamma-ray intensities

Relative gamma intensities were measured by determining the number of counts in each full energy peak observed in the spectrum from the Ge(Li) detector. The relation of efficiency to energy for our detector has been determined by Bear *et al.* [10]). The Compton background under each photopeak was visually estimated. Errors given for the relative intensities reflect statistical uncertainty, error in the efficiency curve, and uncertainty in estimation of Compton background. The latter is the principal source of error. The very weak transitions at 589.3 and 679.4 keV have especially large errors due to uncertainty in the photopeak unfolding procedure. Intensities and errors for all ^{147}Nd gamma rays are given in table 1.

TABLE 2

Upper limits for various gamma transitions

Energy (keV)	Upper limit intensity [g])
41.7 [a])	2.0
78.8 [a,d])	0.2
91 [c,f])	0.7 ($E_\gamma < 91.7$, $E_\gamma > 90.5$)
	2.0 ($E_\gamma < 91.3$, $E_\gamma > 90.9$)
149 [a])	0.1
154.9 [a])	0.1
182 [c,f])	0.1
189 [e])	0.1
191 [a])	0.1
230 [b])	0.2
260 [b])	0.2
270 [a])	0.4
300 [b])	0.3
310 [d,e])	0.3
351 [f])	0.4
508 [f])	0.06
723 [f])	0.01

[a]) Missing transition between levels in our decay scheme.
[b]) Reported in ref. [2]).
[c]) Reported in ref. [3]).
[d]) Reported in ref. [4]).
[e]) Reported in ref. [5]).
[f]) Reported in ref. [6]).
[g]) Intensity relative to 100 for 531 keV gamma-ray.

A search was made for gamma transitions observed by other investigators [2-6]). Upper limits of gamma intensity for transitions above 200 keV were set from data obtained from the Ge(Li) spectrometer. Upper limits below 200 keV were set from data obtained from the curved-crystal spectrometer. An empirical efficiency curve for the curved-crystal spectrometer was constructed using intensity data from the Ge(Li) spectrometer. Upper limits were also established for unobserved transitions between levels in our proposed decay scheme. The upper limits for these transitions are given in table 2.

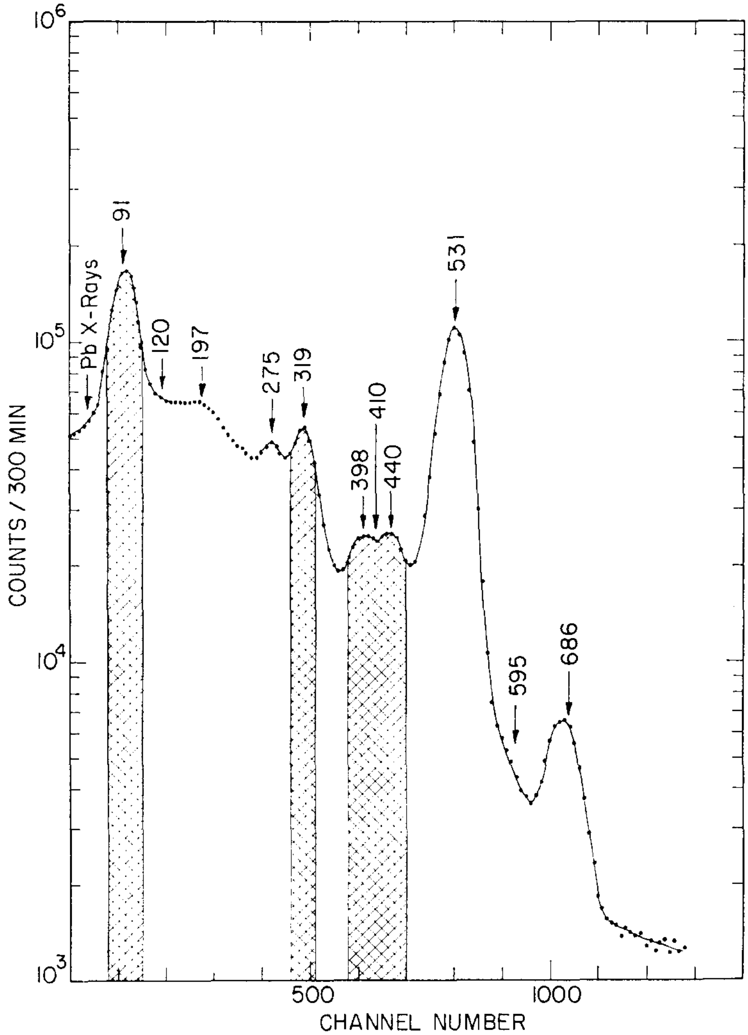

Fig. 3. The pulse-height spectrum of gamma radiation from 50 to 750 keV accompanying the decay of ^{147}Nd as recorded by a 7.6 × 7.6 cm NaI spectrometer. Regions used in gating various coincidence experiments are shown in cross-hatched areas. All energies are in keV.

5. Gamma-gamma coincidence measurements

Gamma-gamma coincidence studies were made with a 7.6 × 7.6 cm NaI(Tl) spectrometer and a Ge(Li) spectrometer having an area of 8 cm^2 and a depletion depth of 0.5 cm. The detectors were oriented at 90° to each other, and the gating pulse for the multichannel analyser was obtained from the NaI detector. The coincidence resolving time was about 50 nsec. An 0.5 μsec delay was introduced to estimate the contribution from random coincidences. The resolution width (fwhm) obtained for

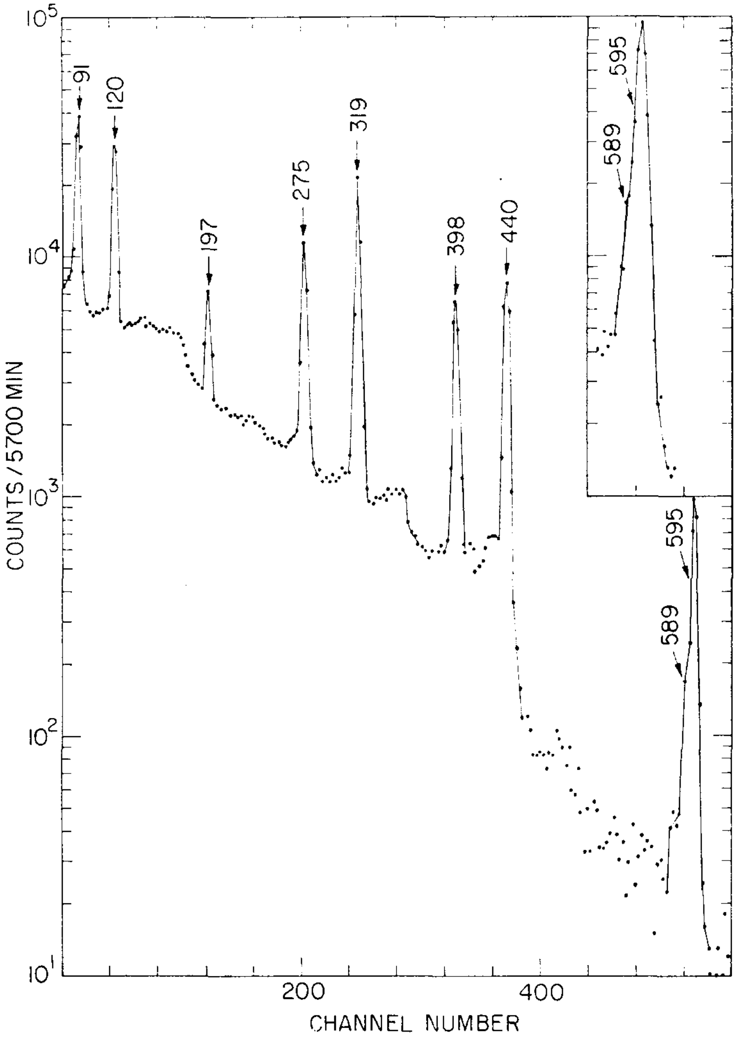

Fig. 4. The pulse-height spectrum of gamma radiation in coincidence with the 91 keV gamma ray. The source distance to the 5 mm Ge(Li) spectrometer was 2 cm. All energies are in keV.

the 531 keV gamma ray from ^{147}Nd was 4.3 keV. All spectra shown are corrected only for random coincidences, and the location of each coincidence gate is shown on the NaI detector spectrum in fig. 3.

The spectrum observed in coincidence with the gamma ray at 91 keV is shown in fig. 4. A true-to-chance ratio of about 30 was used, and no true coincidences were observed above 600 keV. The Compton distribution under the 91 keV photopeak had negligible effect except for the introduction of a peak at 91 keV. Strong coincidences were observed at 120, 197, 275, 319, 398, 440 and 595 keV. A weak coincidence was observed at 589 keV. The 589, 595 keV doublet is illustrated in detail in the inset in fig. 4. The two peaks were not clearly resolved due to the poorer resolution of the coincidence spectra. Their relative intensities were about the same in both the coincidence and singles spectra. The peak at 91 keV was adequately explained by the Comp-

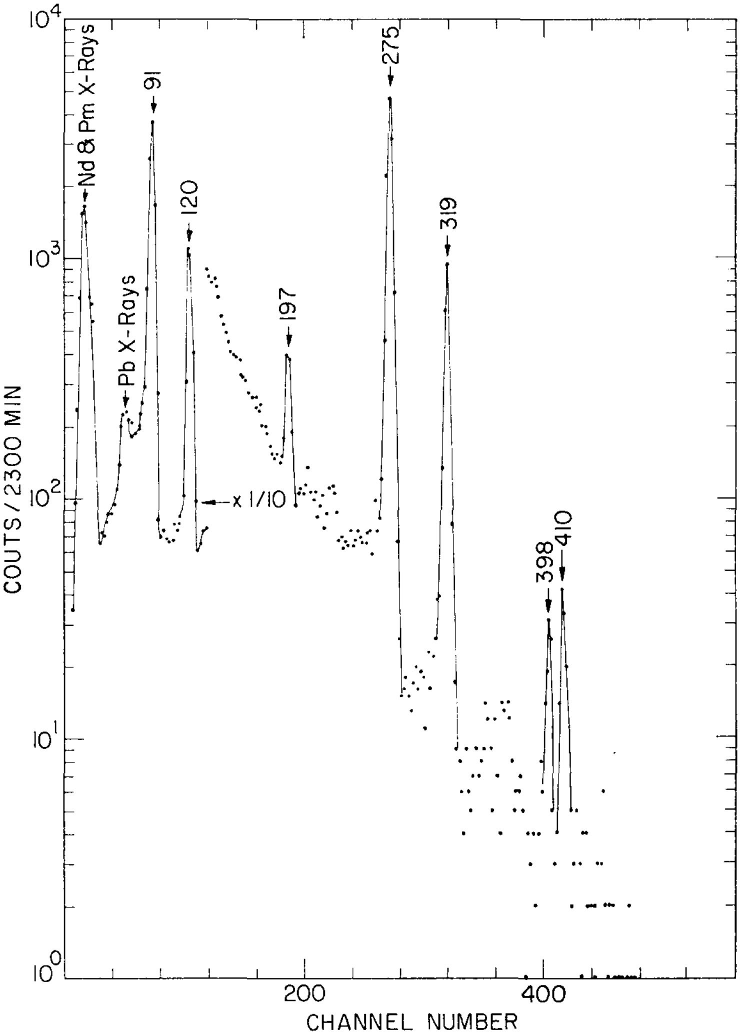

Fig. 5. The pulse-height spectrum of gamma radiation in coincidence with the 319 keV gamma ray. The source distance to the 5 mm Ge(Li) spectrometer was 4 cm. All energies are in keV.

ton background and gave no evidence to support the existence of a second transition at 91 keV populating the 91 keV level.

The spectrum observed in coincidence with the 319 keV gamma ray is shown in fig. 5, and the spectrum observed in coincidence with the three gamma rays at 398,

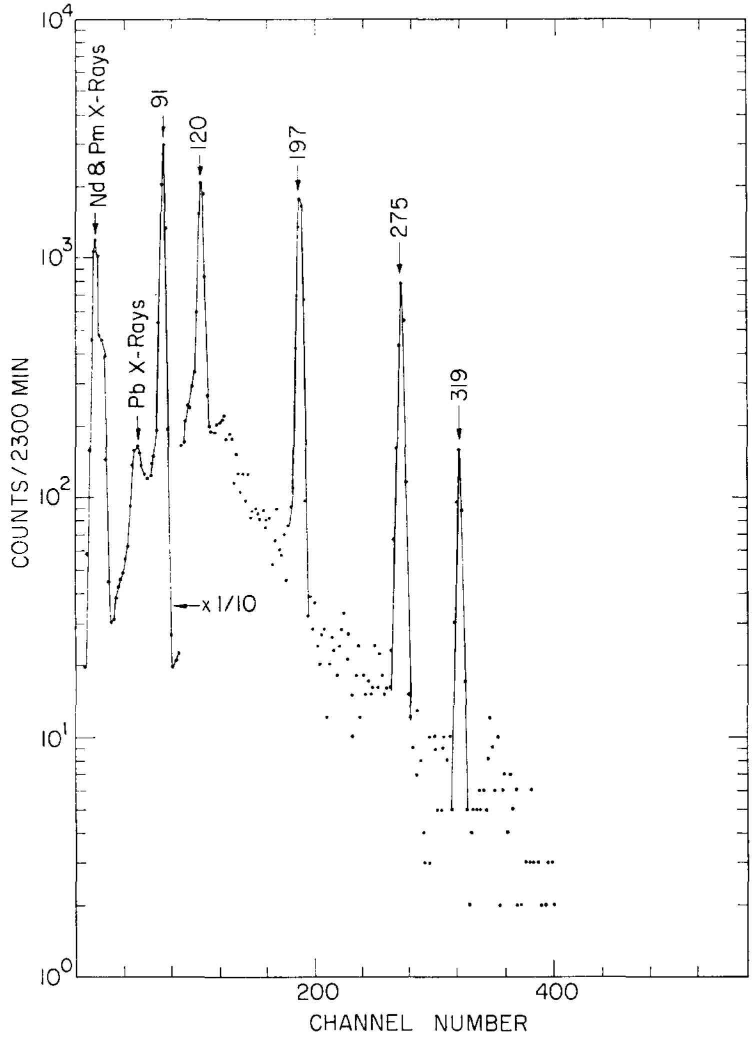

Fig. 6. The pulse-height spectrum of gamma radiation in coincidence with the 398, 410 and 440 keV gamma-rays. The source distance to the 5 mm Ge(Li) spectrometer was 4 cm. All energies are in keV.

411 and 440 keV is shown in fig. 6. These two spectra were measured simultaneously by separate gating of the two halves of the multichannel analyser using a fast-slow coincidence system. A graded lead shield was placed at 45° between the two

detectors to reduce backscattering. In both cases a true to-chance ratio of about 25 was used.

Coincidences between the 319 keV gamma ray and gamma rays at 91, 120 and 275 keV are indicated by strong peaks in the spectrum shown in fig. 5. No true coincidences were observed above 420 keV. The weaker peak at 197 keV arose from coincidences with the Compton distribution from the 398 keV transition which fell under the 319 keV photopeak. Peaks at 319 and 410 keV corresponded to transitions in coincidence with the 275 keV transition. The high energy tail of the 275 keV photopeak fell in the window for the 319 keV photopeak as shown in fig. 3. A small peak at 398 keV was caused from summing of the 91 and 197 keV gamma rays in the NaI detector. Part of this peak fell in the 319 keV gamma-ray photopeak window. Summing also contributed to the peaks at 319 and 410 keV. The height of the 398, 319 and 410 keV peaks relative to the other coincidence peaks was reduced by placing a 1.5 mm Cd sheet over the face of the NaI detector to absorb some of the incoming 91 keV gamma rays thereby verifying the summing mechanism.

Strong peaks at 91 and 197 keV in fig. 6 resulted from coincidences with the 398 keV transition. Weaker peaks at 120 and 275 keV were the result of coincidences with the 410 keV transition. The peak at 319 keV was due to summing of the 91 and 275 keV gamma rays. Insertion of a 1.5 mm Cd sheet reduced the height of the 319 keV peak relative to the other coincidence peaks. In fig. 6 no true coincidences were observed above 330 keV.

One purpose of the above coincidence runs was to search for transitions from the weakly fed level at 680 keV populating the levels at 411, 489 and 531 keV. No evidence for such transitions was found.

6. Decay scheme and discussion

The gamma transition energies and intensities and their coincidence relationships have been interpreted on the basis of the decay scheme shown in fig. 7. Excited states at 91, 411, 531 and 686 keV confirmed the findings of other investigations [1-6]). An excited state at 489 keV is in agreement with the work of several experimenters [2,4-6]). The inclusion of a new level at 680 keV was supported by the observation of two weak gamma transitions having energies of 589.3 and 679.4 keV. No evidence was found for the levels at 182, 230, 289 or 723 keV proposed by various investigators [1-6]).

The spin assignments given in fig. 7 were based primarily on the work of Westenbarger and Shirley [11]) and are discussed in detail below. They also gave mixing parameters for various transitions. The value of Q for the ^{147}Nd decay has been given by Mattauch *et al.* [12]) to be 900±10 keV. Log *ft* assignments were based on the gamma intensity measurements of this investigation. Correction for internal conversion was made assuming all transitions to possess an M1 or E2 character. This assumption was consistent with the spin assignments given in fig. 7. The log *ft* values determined in this investigation are compared to the work of others in table 3. Log *ft* values

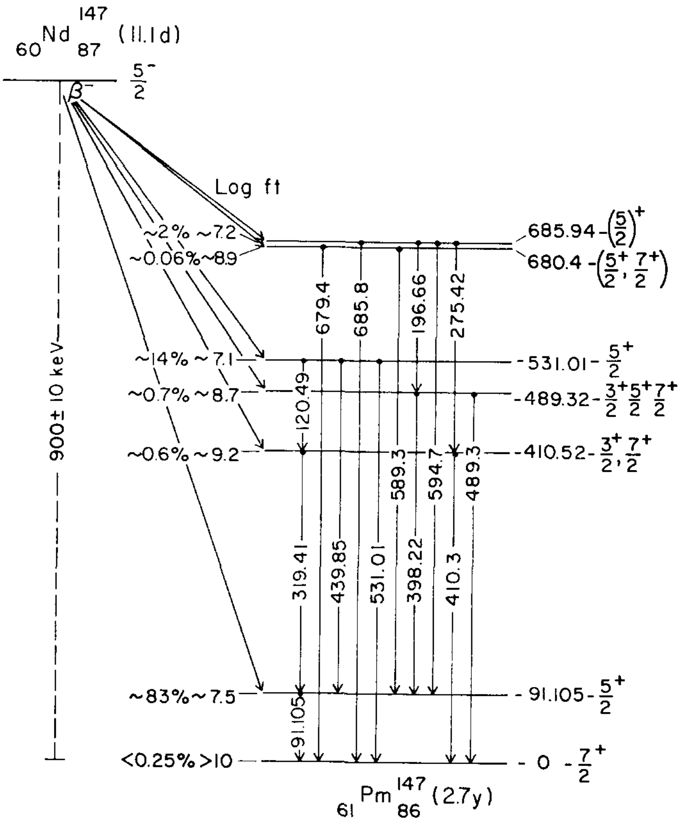

Fig. 7. The decay scheme of ^{147}Nd from the present studies.

TABLE 3

Comparison of log *ft* values reported by various investigators

Beta endpoint (keV) present work	Evans [2]	Wendt *et al.* [3]	Log *ft* Gunye *et al.* [4]	Log *ft* Sharma *et al.* [13]	Župančič [14]	Present work
900			≈ 9.8	> 10 [a]		> 10
809	7.4 [a]	7.6 [a]	7.4 [b]	7.4 [b]	7.5 [a]	7.5 [b]
489			9.0 [b]	9.0 [a]	7.8 [a]	9.2 [b]
411	8.3 [a]	9.0 [a]	8.2 [b]	8.2 [a]		8.7 [b]
369	6.9 [a]	7.3 [a]	7.0 [b]	7.0 [a]	7.0 [a]	7.1 [b]
220						9.8 [b]
214	7.0 [a]	6.5 [a]	7.0 [b]	6.8 [a]	6.4 [a]	7.2 [b]

[a] Log *ft* values obtained from beta spectra measurements.

[b] Log *ft* values obtained from gamma spectra measurements.

for beta decay to levels not observed by us have been omitted. A discussion of the individual levels follows.

The 0 keV *level.* The spin of the ground state of ^{147}Pm has been directly measured by several groups [15-17]) to be $\frac{7}{2}$. The shell model predicts a positive parity for this ground state. Sharma *et al.* [13]) placed an upper limit of 0.25 % on the unobserved beta transition from the ^{147}Nd ground state. The log *ft* for beta decay to the ground state is thus greater than 10. This is unexpected since the spin of the ^{147}Nd ground state has been measured [15,18]) to be $\frac{5}{2}$. The parity of the ^{147}Nd ground state is predicted to be negative by the shell model.

The 91.105 keV *level.* The energy of the gamma transition from the first excited to the ground state was measured to be 91.105±0.0016 keV using the 2 m curved-crystal spectrometer. The value is in fair agreement with the value of 91.05±0.04 keV obtained by Walters *et al.* [19]) using a bent quartz crystal spectrograph. A log *ft* of 7.5 for the beta transition to this level was obtained. This log *ft* limits the spin of the first excited state to $\frac{3}{2}$, $\frac{5}{2}$ or $\frac{7}{2}$. The predominantly M1 character of the 91 keV transition eliminated $\frac{3}{2}$ and designated a positive parity for this state. Westenbarger and Shirley [11]) were able to eliminate $\frac{7}{2}$ on the basis of nuclear alignment studies.

The 410.52 keV *level.* The energy of this level was measured to be 410.52±0.03 keV. This value was obtained by summing the energy of the 319.41 keV transition obtained using the curved-crystal spectrometer with that of the 91.105 keV transition. The cross-over transition at 410.3 keV was also observed. The log *ft* for the beta transition to this level was found to be 9.2. The predominantly M1 nature of the 319 keV transition indicated that $\frac{3}{2}^+$, $\frac{5}{2}^+$ or $\frac{7}{2}^+$ were the only possible assignments for the second excited state. Angular correlation measurements on the 319−91 keV cascade by Bodenstedt *et al.* [20]) and nuclear alignment studies by Westenbarger and Shirley [11]) eliminated $\frac{5}{2}^+$. It was not possible for us to choose between an assignment of $\frac{3}{2}^+$ and $\frac{7}{2}^+$.

The 489.32 keV *level.* The energy of this level was measured to be 489.32±0.07 keV. This value was obtained by summing the energy of the 398.22 keV transition obtained using the curved-crystal spectrometer with that of the 91.105 keV transition. The cross-over transition at 489.3 keV was also observed, but no evidence was found for decay to the level at 410.52 keV. The log *ft* for the beta transition to the 489.32 keV level was found to be 8.7. The predominantly M1 nature of the 398 keV transition indicated that $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$ were the only possible assignments for the 489.32 keV level. It was not possible to narrow this choice further.

The 531.01 keV *level.* The energy of this level was measured to be 531.01±0.04 keV. This value was obtained by summing the energies of the 91.105, 319.41, and 120.49 keV transitions measured with the curved-crystal spectrometer. The cross-over transition at 531.01 keV was observed. A transition at 439.85 keV populating the 91.105 keV level was also observed. No transition was observed to the 489.32 keV level. The log *ft* for the beta transition to the 531.01 keV level was found to be 7.1. This log *ft* limits the spin of the above level to $\frac{3}{2}$, $\frac{5}{2}$ or $\frac{7}{2}$, and the mixed M1E2 character of the 531 keV transition further limits the assignment to $\frac{5}{2}^+$ or $\frac{7}{2}^+$. Westenbarger and Shirley [11]) were able to eliminate $\frac{7}{2}^+$ on the basis of their nuclear alignment measurements and Bodenstedt's [20]) measurement of the angular correlation between the 91 and 440 keV gamma rays.

The 680.4 keV *level.* A new level of energy 680.4±0.7 keV has been observed by us. Its energy was determined by summing the energy of the weak transition at 589.3 keV observed with the Ge(Li) spectrometer with the 91.105 keV transition. A weak cross-over transition at 679.4±1.5 keV was also observed. The placement of this level is supported by observation of coincidences between the 91 and 589 keV gamma-rays but a lack of coincidence between the 91 and 679 keV gamma-rays. No transitions were observed between the 680.4 keV level and levels at 410.52, 489.32 and 531.01 keV. Coincidence measurements gating on the gamma rays at 319, 398 and 440 keV also failed to reveal such transitions. The log *ft* for beta decay to the 680.4 keV level was determined to be 8.9. This log *ft* and the approximate equality of the intensities of the 589.3 and 679.4 keV gamma-rays limits the spin of the level to $\frac{9}{2}$, $\frac{7}{2}$, $\frac{5}{2}$ or $\frac{3}{2}$. The approximate equality of the intensities of the above gamma rays favours a mixed M1E2 character for both. This "weak" argument favours a $\frac{5}{2}^+$ or $\frac{7}{2}^+$ character for the 680.4 keV level but negative parity or spin of $\frac{3}{2}$ or $\frac{9}{2}$ cannot be absolutely excluded.

The 685.94 keV *level.* The energy of this level was measured to be 685.94±0.04 keV. The value was obtained by summing the energies of the transitions at 91.105, 319.41 and 275.42 keV. These values were all obtained using the curved-crystal spectrometer. Transitions were observed to all levels except the ones at 531.01 and 680.4 keV. Coincidence measurements using gates at 319, 398 and 440 keV supported the absence of such transitions. The log *ft* for beta decay to the 685.94 keV level was determined to be 7.2. This log *ft* limits the spin of the above level to $\frac{3}{2}$, $\frac{5}{2}$ or $\frac{7}{2}$, and the mixed M1E2 character of the 686 keV transition further limits the assignment to $\frac{5}{2}^+$ or $\frac{7}{2}^+$. Shirley and Westenbarger [11]) on the basis of nuclear alignment studies favoured $\frac{5}{2}^+$ but were not able to definitely rule out $\frac{7}{2}^+$.

No evidence from this investigation supported the existence of levels at 182, 230, 289 and 723 keV proposed by various investigators [1-6]). Upper limits for various transitions proposed to feed and depopulate these levels are given in table 2. It has been proposed [3,6]) that the level at 182 keV decays by emission of gamma rays at 91 and 182 keV. Although a second transition at 91 keV cannot be completely ruled out, narrow limits on its energy and intensity have been set by use of the curved-crystal spectrometer. Gamma transitions at 351 and 508 keV proposed [6]) to feed the 182 keV level were not observed in this investigation.

A level at 230 keV was postulated [2]) to depopulate by emission of a 230 keV gamma ray and be fed by gamma rays at 260 and 300 keV. We did not observe these gamma rays. It has been proposed [1,3]) that a level at 290 keV is populated by the 398 keV transition and depopulated by the 197 keV transition. In our decay scheme the order of these two transitions has been reversed giving a level at 489 keV. The observation of a transition from the 489 keV level to the ground state supported this order. A level at 723 keV has been proposed by three observers [4-6]). A 723 keV gamma-ray has been proposed [6]) to depopulate this level while others [4,5]) have proposed a 310 keV gamma-ray to depopulate it. We have not observed the transitions proposed above.

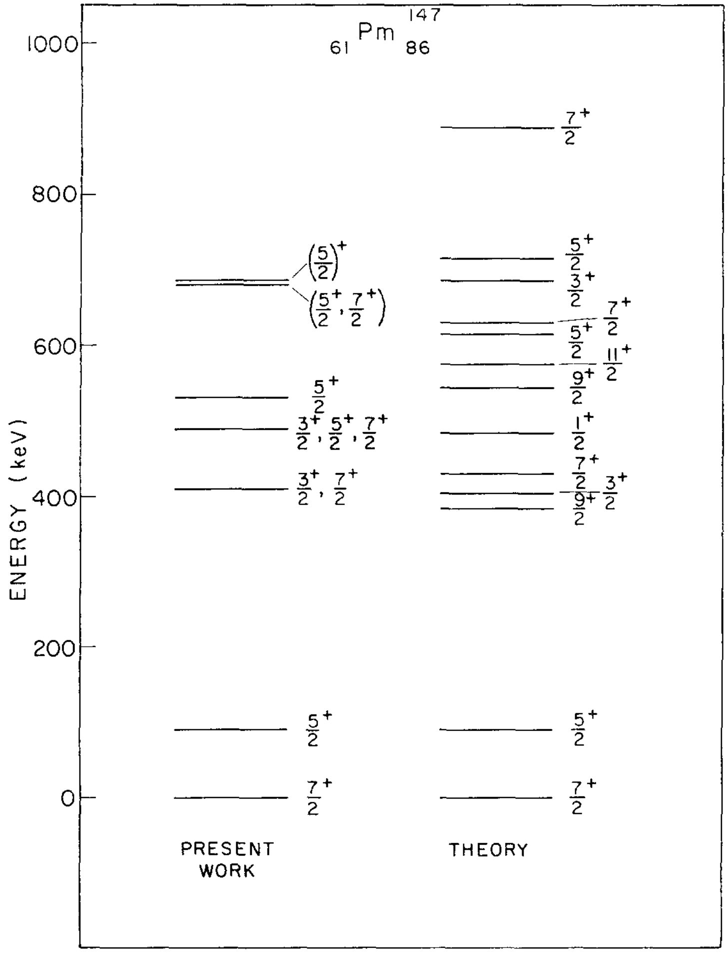

Fig. 8. Comparison of the level scheme of ^{147}Pm from the present work with predictions of intermediate coupling theory.

7. Comparison with predictions of intermediate coupling theory

The level spectra for ^{147}Pm has been calculated by Choudhury and O'Dwyer [21]) within the framework of the intermediate coupling approach in the unified model. In fig. 8 their predictions are compared with the results of this experiment. The theory is in agreement with the gross features of the observed spectrum.

Transitions populating both the ground and first excited states have been observed from each of the higher levels. Since lifetimes for these states were unknown it was of interest to compare the experimental intensity ratios for transitions populating the ground and first excited states with the theoretical predictions. The intensity ratio of the transitions depopulating the 411 keV state was measured to be 7.4×10^{-2}. Choudhury and O'Dwyer associated this state with their first $\frac{3}{2}^+$ state and calculated a ratio of 6.6×10^{-1}. It might be possible to associate this level with the theory's second $\frac{7}{2}^+$ state but transition probabilities for that state were not available.

Choudhury and O'Dwyer [21] associated their second $\frac{3}{2}^+$ state with our level at 686 keV. They obtained an intensity ratio of 5.5×10^{-4} while we measured the ratio to be 3.1. The $\frac{3}{2}^+$ state predicted by theory is therefore not identical with the state at 686 keV but may represent a state not observed by us.

The beta transition to the first excited state of ^{147}Pm has a log *ft* of 7.5 while a beta transition to the ground state has not been observed. Similar highly hindered beta transitions have been observed in the beta decay of ^{149}Nd and ^{143}Pr. A qualitative explanation of these hindered transitions has been given by Beekhuis *et al.* [22] on the basis of the strong *jj*-coupling shell model.

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