both of these gamma rays are converted in cadmium. Therefore neither can follow an isomeric transition in In^{110m}.

The present energy measurements of the 0.1200-, 0.4614-, and 0.5840-Mev transitions indicate that the two former transitions are not in cascade, in parallel with the latter, as proposed by Yoshizawa.[1]

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The author would like to thank Dr. E. Bleuler, who suggested this problem, for his interest and helpful discussions. The advice of Dr. H. J. Yearian and the use of his photodensitometer is gratefully acknowledged. Dr. R. Nakasima, National Academy of Sciences, kindly furnished a translated copy of reference 5.

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Decay of Neodymium-147

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The decay of Nd^{147} has been investigated using scintillation spectroscopy and coincidence technique. The following sequences of gamma emission have been uniquely established: 91-kev gamma ray is in coincidence with 120, 199, 277, 322, 400, 442, and 599-kev gamma rays; 120-kev gamma ray with 322- and 413-kev gamma rays; 199-kev gamma ray with 400- and 491-kev gamma rays; 277-kev gamma ray with 322- and 413-kev gamma rays; and 310-kev gamma ray with 322- and 413-kev gamma rays. On the basis of these gamma-gamma sequences, the levels of Pm^{147} at 91, 413, 491, 533, 690, and 723 kev above the ground state are unambiguously established. A critical analysis of the observed coincidence spectra shows that the levels at 182 and 230 kev, suggested by other workers, either do not exist or, if they exist, are not populated by any beta transition of intensity more than a percent or by any gamma transition from other higher energy levels, of intensity more than 0.1%.

INTRODUCTION

THE decay of 11-day neodymium-147 has been repeatedly studied by various workers.[1–10] It has been investigated by various techniques but a unique decay scheme is not yet established.[10] The levels of Pm^{147} at 91, 413, 533, and 690 kev, suggested by Hans *et al.*[2] on the basis of gamma-gamma coincidence measurements, have been confirmed. The level scheme is shown in Fig. 1. An additional gamma-ray cascade of 199- and 400-kev gamma rays, introduced by Cork[5] *et al.* between the 91- and 690-kev levels, is also confirmed by later workers.[9] But the order of emission of 199- and 400-kev gamma rays and consequently the location of an additional level at 290 or 491 kev remained uncertain. A second additional level at 230 kev was suggested by Evans[6] to accommodate the gamma rays of energy 230, 260, and 300 kev which were originally reported by Rutledge *et al.*[1] Recently the beta spectrum of this activity has been investigated by Wendt *et al.*[10] On the basis of the analysis of the beta spectrum they suggest a level at ~182 kev being populated by a beta transition of intensity about ten percent and decaying mainly by a 91-91 kev gamma-ray cascade to the ground state; thus they postulate two 92-kev gamma rays. In view of this prevailing situation it was

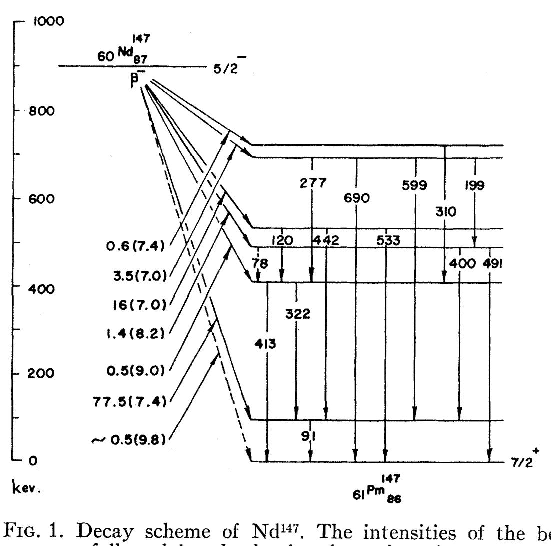

FIG. 1. Decay scheme of Nd^{147}. The intensities of the beta groups are followed by the log*ft* values given in parentheses.

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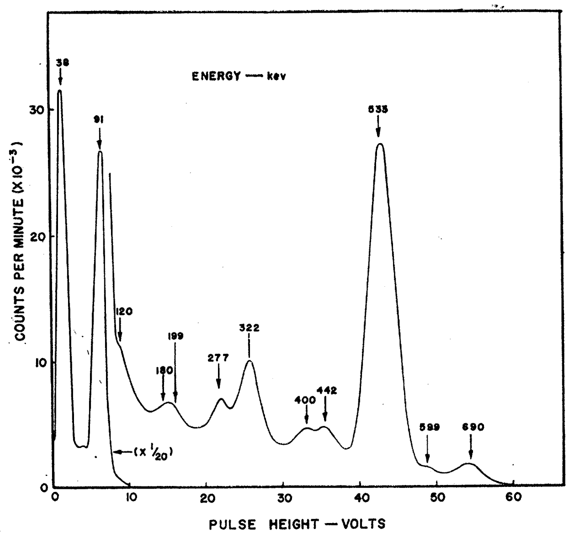

FIG. 2. The gamma-ray spectrum of Nd^{147} as observed with a 2-in. diam$\times$2-in. thick NaI(Tl) crystal.

considered useful to look into the decay of this isotope by a systematic study of gamma-gamma coincidences and thus an attempt has been made to establish the energy levels rather unambiguously.

MEASUREMENTS

Sources of Nd^{147} were obtained by irradiating spec-pure samples of natural neodymium oxide in Apsara reactor (Trombay) for a period of 12 to 15 days. In some cases the active sample was purified in an ion exchange column to remove other activities, mainly of Pm, while in other cases the sample was allowed to cool for a period of four to five weeks so that the gamma spectrum of the sample looked free from any detectable contribution of other activities of shorter life. The activity of this isotope, produced in fission products, was also obtained from Oak Ridge for a part of the investigations.

The gamma-ray spectrum from a purified source was observed with a 2-in. diam$\times$2-in. thick NaI(Tl) crystal scintillation spectrometer which is shown in Fig. 2. In addition to the prominent full-energy peaks at 38 (K x ray of Pm), 91, 277, 322, 533, and 690 kev, there are indications for the presence of 120, 199, 400, 442, and 599-kev gamma rays. The energy values of these gamma rays are taken from various measurements with beta spectrometers.[3,5]

INTEGRAL GAMMA SPECTRUM STUDY

To investigate the various levels of Pm^{147} excited in this decay by direct beta transitions, the integral spectrum of its gamma transitions was studied in a total gamma-ray absorption spectrometer. The NaI(Tl) crystal used was 3 in. diam$\times$3 in. thick with an axial well $\frac{1}{4}$ in. diam$\times 1\frac{1}{2}$ in. deep. The source was kept in a glass tube of about 1-mm wall thickness.

The integral gamma spectra with different absorbers are shown in Fig. 3. The Pm K x-ray peaks are not seen in the spectrum due to the lower pulse height cutoff of the analyzer. In understanding such integral spectra the large internal conversion coefficient ($\sim$1.7) of the 91-kev transition[3] should be taken into account. The gamma rays feeding the 91-kev level may sometimes combine with a 91-kev gamma photon or a 38-kev K x-ray photon corresponding to K internal conversion, or may not combine with any photon corresponding to the internal conversion and subsequent nonradiative or very low energy radiative transitions in the atom. The spectrum shown in the figure with the source only in the glass tube, curve A, shows the presence of a highest energy level at 723 kev hitherto unreported. The peak at 690 kev is in agreement with the earlier reported level at 690 kev.[2,5] This level is reported to decay by 599-91, 199-400-91, and 277-322-91 kev cascades and a 690-kev crossover gamma transition.[5] The expected satellite peak corresponding to the 38-kev x-ray emission instead of 91-kev gamma emission, at 650 kev has filled up the valley of 690-kev peak. This is confirmed by the appearance of the valley in curve C when the x rays are absorbed and the 599-kev peak becomes prominent. The peak at 533 kev corresponds to a level which is reported to decay[2] by 120-322-91 and 120-413 kev cascades and a 533-kev crossover gamma transition to the ground state. The satellite peaks do not have prominence due to the intense ground-state transition. The behavior of the spectrum in the energy region of 400 to 480 kev is complex. In the spectrum A, the peak at 440 kev is due to the combination of 400-38 kev photons.[5] The combination of 442-38 kev photons[2] fills up the valley at 480 kev. When an ab-

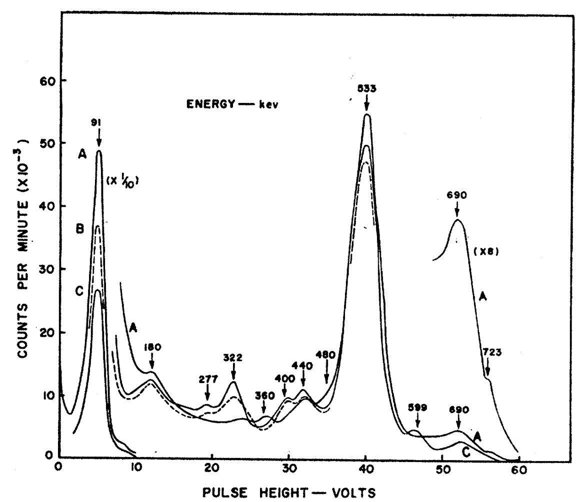

FIG. 3. The total absorption gamma-ray spectrum as seen in a 3 in. diam$\times$3-in. thick NaI(Tl) crystal with the source inside the well of $\frac{1}{4}$-in. diam$\times 1\frac{1}{2}$ in. deep. Curve A—Source in a glass tube of 1-mm wall thickness. Curve B—With 0.5-mm thick copper surrounding the source tube. Curve C—With 1.25-mm thick copper surrounding the source tube.

sorber is introduced (curve B), a new peak appears at 400 kev. The number of pulses at 480 kev goes down. Since the influence of the x-ray absorption in the case of two cascades of 400-38 and 442-38 kev gamma–x ray is equal and the intensities of the 400- and 442-kev gamma rays are almost equal, the number of pulses at 440 kev in curves A and B remains equal. The absorption of the 91-kev gamma ray in the spectrum C brings in a further increase of pulses at 442 kev. The small peak at 360 kev in the spectrum A is due to the combination of 322-38 kev photons. This peak disappears when the x rays are absorbed. The peaks at 322 and 599 kev acquire prominence when the 38-kev x rays and 91-kev gamma rays are absorbed in the spectrum C.

A small peak at 180 kev sitting over a continuum in the spectrum *A* could be due to a level at 180 kev[10] or due to the back-scattering of the intense 533-kev gamma ray from the glass tube. The level at 180 kev suggested by the earlier workers[10] is supposed to decay mostly by a 91–91 kev gamma-ray cascade. But the behavior of the peak with the absorbers in the spectra B and C does not support this view. When an absorber is introduced, the number of pulses in the energy region between 91 and 180 kev goes down quickly, showing that they are due to the combination of 91-kev gamma ray with x rays corresponding to the conversion of all other gamma rays in coincidence with it and low-energy bremsstrahlung associated with the intense beta group feeding that level. But the peak at 180 kev becomes prominent although the 91-kev radiation is half absorbed in the spectrum C. This confirms the view that the 180-kev peak is due to the backscattering of the 533-kev gamma ray.

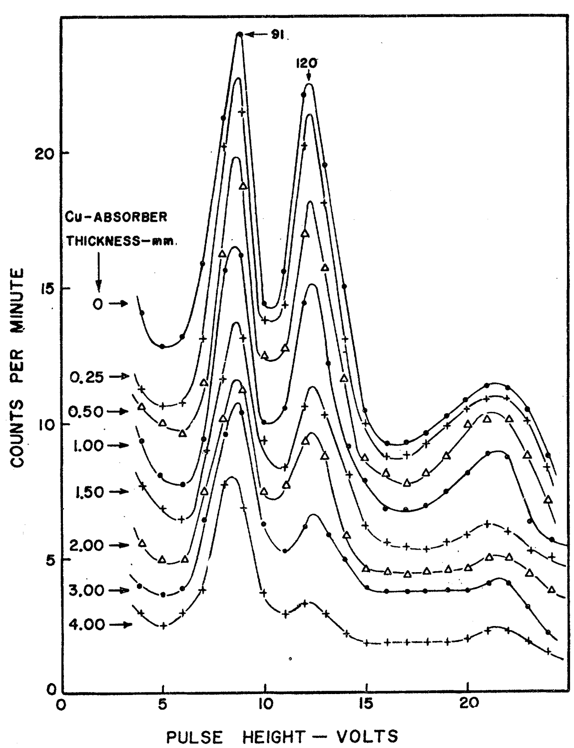

FIG. 4. The pulse-height distribution in coincidence with the gate channel fixed in the region of 85 to 95 kev. The variation of the spectrum is seen when Cu absorbers of various thicknesses are introduced in the gate detector side.

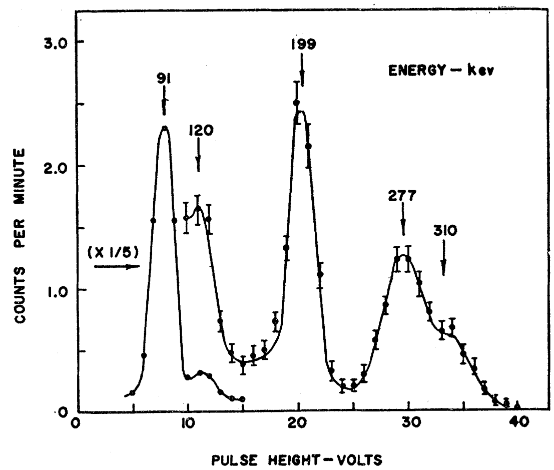

FIG. 5. The pulse-height spectrum due to the gamma rays in coincidence with the pulses in 390- to 420-kev region.

GAMMA-GAMMA COINCIDENCE STUDY

The coincidence studies of the various gamma rays were carried out by two scintillation spectrometers having $1\frac{3}{4}$-in. diam×2-in. thick NaI(Tl) crystals as gamma ray detectors. They were operated in coincidence by the standard fast-slow coincidence technique. The resolving time was normally kept about $2\tau=0.06$ μsec. Two geometrical arrangements were used to observe the coincidence spectra. In the head-on geometry, the detectors viewed the source through lead cones each having an opening of 5-mm diameter at the apex and subtending a half-angle of about 80°. In the right-angle geometry, the two crystals were shielded from one another by a lead wall of 2-cm thickness. The latter geometry was used to check the results obtained in the former geometry. A single-channel analyzer was used with one of the detectors to select the region of pulse-height spectrum with which the coincidences were to be studied. The coincidence pulse-height spectrum from the other detector was analyzed in a Gatti-type twenty-channel pulse-height analyzer.

The suggested existence of two 91-kev gamma rays in coincidence is further investigated by a careful study of the spectrum in the low-energy region in coincidence with the 91-kev pulses. Figure 4 shows the coincidence spectra recorded with different copper absorbers of various thicknesses. The absorbers were introduced on the gate detector detecting the 91-kev pulses. The coincidences at 91 kev shown in the above figure could be due to three different processes: (a) a 91-kev gamma ray entering the gate detector and another gamma ray of similar energy entering the scanning detector; (b) a 91-kev gamma ray entering the gate detector and higher energy gamma rays that are in coincidence with 91-kev gamma, producing Compton pulses in the 91-kev region in the scanning detector; and (c) higher energy gamma rays, coincident with 91 kev, producing Compton pulses in the 91-kev region, entering the gate detector, while a 91-kev photon enters the scanning detector. The (b) and (c) class pulses also includes the effect due to the iodine K-x-ray escape peak of 120-kev radiation. The (a) and (c) class pulses produces a peak at 91 kev while the (b) class forms a continuum. When an absorber is introduced on the gate detector side, the absorption of (a) and (b) class pulses will follow the absorption of 91-kev radiation while the (c) class pulses will follow the absorption rate of high-energy gamma rays.

In view of the above situation, the coincidence counting rate in the 91-kev region is divided into two parts by analyzing the observed coincidence spectra. The number of pulses belonging to the class (b) is estimated by extrapolating the Compton distribution of coincident spectrum of the higher energy gamma rays as observed in the actual spectrum of the scanning detector. Also the contribution due to the escape peak of the 120-kev gamma ray is taken into account. The contribution of the pulses of classes (a) and (c) is thus estimated. Since the rate of absorption of the two types of pulses (a) and (c) is vastly different, one following the absorption of 91 kev and the other following that of higher energy gamma rays, the rate of absorption of these pulses in the spectrum is further analyzed. The analysis shows that the number of pulses belonging to the class (a) may arise due to a radiation of energy around 91 kev, of intensity at most one percent of the total 91-kev radiation. These 91-91 kev coincidences could further be due to a genuine second 91-kev gamma ray or the 78-kev gamma transition between the 491- and 413-kev levels shown in Fig. 1, or the external and internal bremsstrahlung associated with the intense beta group feeding the 91-kev level. Unfortunately it has not been possible to associate conclusively these observations with each of the above effects quantitatively.

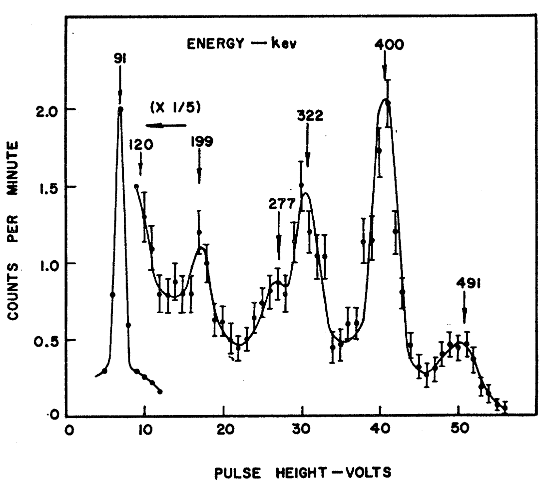

FIG. 6. The pulse-height spectrum of the gamma rays in coincidence with 199-kev gate pulses.

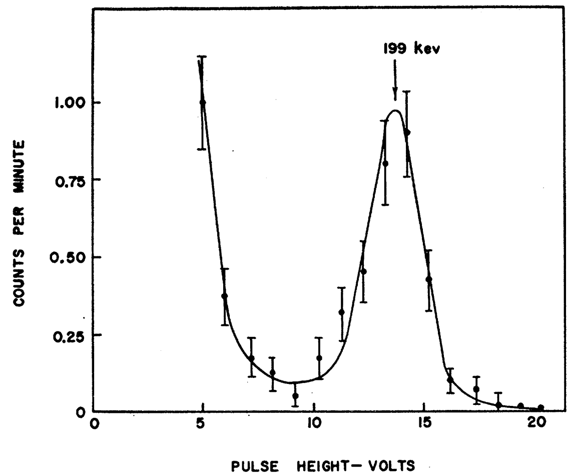

FIG. 7. The pulse-height spectrum in coincidence with 491-kev gate detector pulses.

To establish the level at either 290 or 491 kev, involved in the emission of 199-400 kev gamma-ray cascade, a systematic study of the coincidences was undertaken. The spectrum observed in coincidence with the gate channel fixed in the 390- to 420-kev energy region is shown in Fig. 5. The peaks at 120 and 277 kev are due to the detection of the 413-kev gamma ray, originating in the transition from the 413-kev level to the ground state,[2,7] being detected in the gate channel. The peak at 310 kev could arise from the level at 723 kev, observed in the integral spectrum, feeding the 413-kev level. The other peaks at 91 and 199 kev are due to these gamma rays being in coincidence with 400-kev radiation.[5] The intensity of the 91-kev peak is much larger than that of the 199-kev peak; and the 413-kev gamma ray is not in coincidence with the 91-kev transition. Hence it is obvious that the 199-kev radiatiin precedes the 400 kev transition, suggesting a level at 491 kev.

To confirm the level at 491 kev, the gamma-ray spectrum in coincidence with 199-kev gamma ray, as observed in head-on geometry, is shown in Fig. 6. The peak at 400 kev is followed by another one at 491 kev. The cascade nature of the 199-491 kev gamma rays is further confirmed by the observed spectrum in coincidence with the 491-kev gamma rays which shows a peak at 199 kev in Fig. 7. The rise of coincidences in the 91-kev region is due to the detection of the 442-kev gamma ray in the 491-kev channel.[2,7]

In Fig. 6 it is seen that there are peaks at 200, 277, and 322 kev in coincidence with the 199-kev gamma ray. To investigate the genuineness of the coincidence of these gamma rays with the 199-kev radiation, the spectra in coincidence with these gamma rays are also

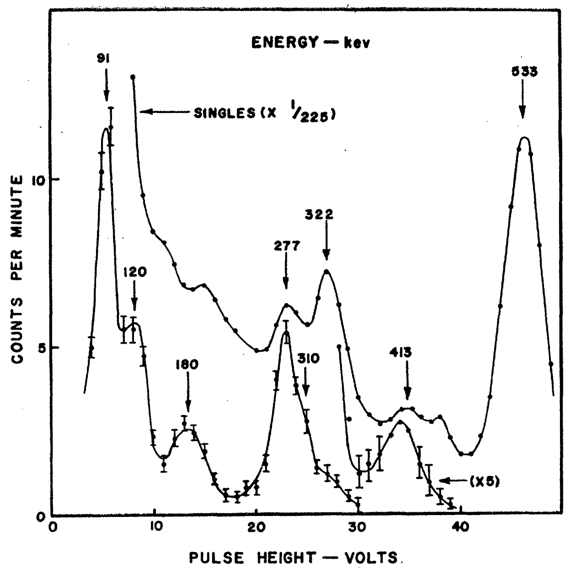

FIG. 8. The pulse-height spectrum in coincidence with 322-kev gate detector pulses. The singles spectrum is also seen for energy comparison.

studied. Figure 8 shows the gamma-ray spectrum in coincidence with the 325-350 kev energy region as observed in head-on geometry. The peaks at 120 and 277 kev confirm the results of the earlier workers.[2,7] The presence of a new peak at 310 kev is also seen. This substantiates the view that the 310-kev gamma ray terminates at the 413-kev level. The presence of a peak at 413 kev is due to the detection of the 310-kev gamma ray in the gate channel. The peak at 180 kev is due to the backscattering of the 533-kev gamma ray and it vanishes when the spectrum is observed in right-angle geometry.

Figure 9 shows the spectrum in coincidence with the 250–380 kev energy region. The peaks at 322 and 413 kev confirm the results of earlier observations (Figs. 5 and 8). Also it is interesting to note that there is no peak at 199 kev. The absence of a peak at 199 kev suggests that the peak at 277 kev obtained in the spectrum in coincidence with 199 kev is due to the Compton pulses of the 322- and 413-kev gamma rays being detected in the 199-kev gate channel. The small peaks at 120 and 277 kev are due to the detection of the 322-kev gamma ray in the gate channel.

Figure 10 shows the spectrum in coincidence with the fixed channel looking into the pulses of energy 120-135 kev. The peaks at 91, 322, and 413 kev confirm the earlier observations. The small peak at 277 kev is due to the detection of the 322-kev gamma ray in the gate detector through a Compton process. It is interesting to note that there is no peak at 199 kev. Also it can be noted that the ratio of the intensities of the 322- and 413-kev peaks is the same as in the case of these peaks in coincidence with the 277-kev gamma ray.

The gamma-ray spectrum in coincidence with 91-kev pulses is shown in Fig. 11. The gate channel was fixed at 85–95 kev region. The contribution due to the 120-kev gamma ray was mainly due to its iodine K x-ray escape peak and their number was small compared to the proper 91-kev pulses. The Compton contribution of other higher energy gamma rays was also comparatively small. The coincidence spectrum shows prominent peaks at 120, 199, 277, 322, and 599 kev. The peak at 599 kev confirms the view that it is a radiation from 690-kev level to the 91-kev state. Thus it is a crossover transition of the 199–400 and 277–322 kev gamma-ray cascades. The peak in the region of 400–442 kev is complex, consisting of these two gamma rays. The peak at 442 kev similarly suggests that it is due to the cascade nature of the 442-91 kev gamma rays, the 442-kev gamma ray being a crossover transition of the 120-322

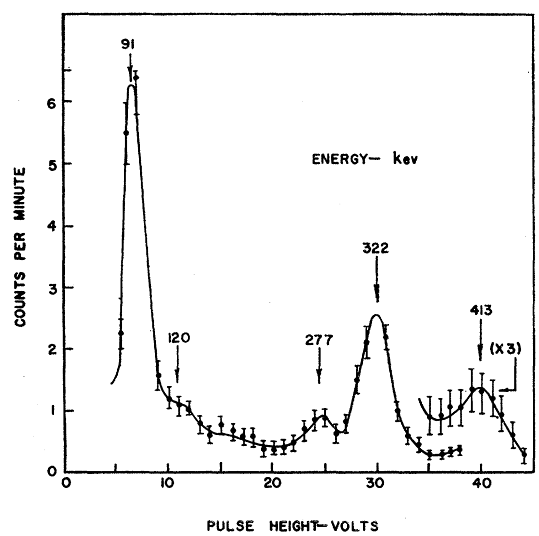

FIG. 9. The pulse-height spectrum in coincidence with 277-kev energy region.

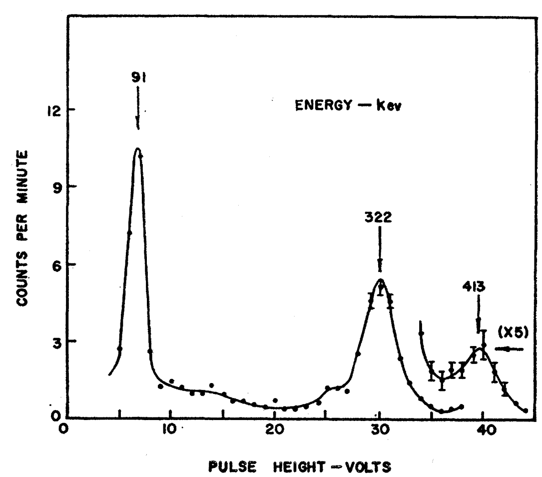

FIG. 10. The pulse-height spectrum in coincidence with 120-kev energy region.

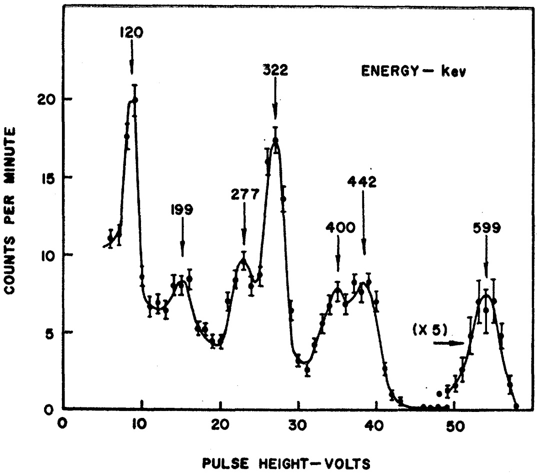

FIG. 11. The pulse-height spectrum in coincidence with 91-kev gamma-ray pulses.

kev gamma-ray cascade. The other peaks at 120, 199, 277, 322, and 400 kev confirm the location of these gamma transitions to be among levels situated above the 91-kev state.

The presence of a 78-kev gamma ray due to a transition from the 491- to the 413-kev state has been searched for by comparing the relative intensities of 277- and 322-kev gamma rays when the gate channel was moved in the 80–90 kev energy region. This did not yield any positive conclusion.

The level at 230 kev introduced by Evans[6] does not have any previous support of experimental evidence. The gamma rays of energies, 230, 260, and 300 kev are not confirmed by any other worker. The coincidence nature of these gamma rays, as proposed by Evans, is not observed in any of the present coincidence studies, thereby ruling out the level at 230 kev.

The intensities of the various gamma transitions have been estimated with the help of the spectrum shown in Fig. 2 and other coincidence spectra. Using the intensities of the gamma transitions, the intensities of the various beta groups feeding the 91, 413, 491, 533, 690, and 723-kev levels have been estimated assuming that no observed beta transition of intensity more than a percent goes to the ground state.[10] These estimates are shown in Table I along with the logft values.

TABLE I. Intensities of the beta and gamma transitions in the decay of Nd^{147}.

Maximum energies of beta groups (kev)	Intensities of beta groups per thousand disintegrations	logft	Energies of associated gamma rays (kev)	Photons per thousand disintegrations
187	6	7.4	310	6
220	35	7.0	690	10
			599	5
			277	14
			199	6
377	160	7.0	533	125
			442	20
			120	8
419	14	8.2	491	3
			400	16
497	5	9.0	413	7
			322	32
728?	<10	>9	~91?	<2.5
819	775	7.4	91	275
910	~5	~9.8	...	...

In view of the proposed scheme for the levels of Pm^{147} and the coincidence spectra reported here, some of the gamma-gamma angular correlation studies reported by the earlier workers[4,9] are in error. The orbital assignments to the levels of Pm^{147} can only be done by angular correlation measurements taking into account the contributions of the various cascades in the detectors.

ACKNOWLEDGMENTS

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