Beta Spectra of Neodymium-147

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The beta spectra of Nd^{147} have been studied with a Siegbahn-Slätis magnetic spectrometer. It has been observed that the first-forbidden beta spectrum, feeding the 91-kev level of Pm^{147}, is nonunique, nonstatistical in shape. The beta spectrum feeding the 531-kev level is of statistical shape within the experimental limits of error. The intensity of the beta transition proceeding to the ground state of Pm^{147} is $<2.5\times10^{-3}$ per disintegration.

INTRODUCTION

THE beta spectrum of Nd^{147} has been investigated by many workers[1–5] with a view to analyzing the various groups of beta transitions directly populating the excited states of Pm^{147}. These experiments have mainly supported the location of the levels at 91, 410, 531, and 686 kev as shown in Fig. 1, to which the beta transitions directly proceed. In view of the measured spin values for the ground states of Nd^{147} and Pm^{147}, as $\frac{5}{2}$ and $\frac{7}{2}$, respectively,[6–8] a direct beta transition between these states of partial half-life about 10 days, corresponding to a $\log ft$ value of about 7.5 for the first-forbidden transition, is expected. No such beta transition is observed from the Nd^{147} activity of half-life 11 days. The lowest limit of the partial half-life for the above transition is recently estimated to be $\sim$3 yr, corresponding to an intensity limit of one percent.[4] In view of this it was considered desirable to look for any positive observation of the beta decay proceeding to the ground state, so that the retardation factor for this transition could be estimated.

Apart from the above well-established levels, there have been various suggestions for the energy levels at 182, 290, and 232 kev by different workers.[1,2] The last two levels were suggested on the basis of energy summation rules. Wendt and Kleinheinz,[4] from their study of the beta spectrum of Nd^{147} and the beta-gamma coincidences, have claimed an inner beta group of end-point energy $\sim$719 kev and intensity of $\sim$10% proceeding to a proposed level at $\sim$182 kev in Pm^{147}. This level, as they suggest, decays mainly by the emission of a 91–91 kev gamma-ray cascade. The recent gamma-gamma coincidence studies of Gunye *et al.*[9] do not provide any evidence for the presence of any of the above proposed levels. Since the suggested decay process of a 91–91 kev gamma-ray cascade does not exist, nor there is any evidence to show that there are two closely spaced 91-kev gamma transitions,[5] the explanation of the observed beta spectrum as complex seems to be in error. Hence the shape of the beta spectrum in the energy region of 500 to 800 kev has been studied both by direct and coincidence methods.

The shape of the beta spectrum feeding the 531-kev state of Pm^{147} is studied by a coincidence method, mainly with a view to confirming its statistical nature.

MEASUREMENTS

Active samples of Nd^{147} were obtained from Oak Ridge in a carrier-free state, produced from fission products. It was found necessary to purify these samples in an ion exchange column. In the first purification, the lower Z side of the activity peak was chosen. The chosen sample was further purified after addition of about 5 mg of praseodymium oxide as a retainer for any

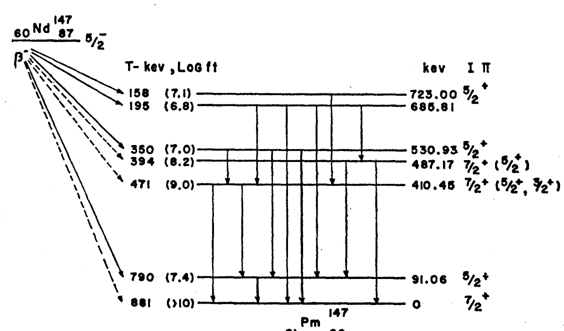

FIG. 1. Energy levels of Pm^{147} with assigned spin values. The end-point energies of the various beta groups followed by $\log ft$ values in parenthesis are also shown. (The spin value for 723 kev level is to be read for 685.81 kev level).

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praseodymium activity. In this way sources of satisfactory purity were obtained. For a part of the investigations, enriched samples of Nd^{146} were irradiated in the Oak Ridge reactor for a period of 15 days. The active sample was purified in an ion exchange column.

Ground-State Beta Transition

The Siegbahn-Slätis beta-ray spectrometer was set for about 1.5% transmission and momentum resolution of 2%. The electrons were detected in a 3-mm-thick anthracene crystal coupled to a photomultiplier tube through a 9-in. light guide. The pulses in the scintillation spectrometer were further analyzed. The pulses corresponding to full-energy peak were counted alone by adjusting the discriminator bias at each momentum setting of the magnetic spectrometer. The method of selecting the discriminator level was well studied with the help of the Sr^{90} beta spectrum. The magnetic spectrometer was set at various energies in the region of 300 to 1000 kev and the pulse-height distribution in the scintillation spectrometer was observed, as is shown in Fig. 2. It was seen that a fraction, 0.89 ± 0.01, of the total number of pulses produced in the anthracene crystal lie in the full-energy peak; and this factor does not vary more than the limits stated in the above energy region. Thus, by following the above procedure of discrimination of pulses, the efficiency of electron detection remained unchanged in the energy region of interest. It considerably helped in reducing the background counts near the trailing edge of the spectrum, while observing the low-intensity ground-state transition.

The beta spectrum observed in the above manner, in the energy region beyond 600 kev, is shown in Fig. 3. It is seen that the intensity of the beta spectrum, although small, continues to persist beyond 800 kev and up to 900 kev. This may be attributed to the beta transition proceeding to the ground state of Pm^{147}. However, the contribution of the intense beta group of maximum energy 790 kev beyond the end point due to the "finite" resolution of the spectrometer is difficult to estimate. Hence, from this investigation, an upper limit of intensity of 0.25% for the possible ground-state transition is estimated.

Beta Transition to the 91-kev Level

About 77% of the beta decay proceeds to the 91-kev level.[9] The beta spectrum above 500 kev belongs purely to this transition except for a small fraction possibly going to the ground state. To investigate this spectrum the spectrometer performance was studied by investigating the beta spectrum of Au^{198}.

The source of Au^{198} was produced by neutron irradiation of spec-pure Au in the Apsara reactor (Trombay) for a period of 24 hr. Active gold was dissolved in aqua regia and a source of 2-mm diameter was prepared on a Tygon film over an insulin drop of the same diameter. The thickness of the source was adjudged to be less than 100 μg/cm^2 by a comparison method.

The spectrometer was adjusted as described earlier. At the beginning of every measurement it was demagnetized to avoid the influence of the residual magnetic field. It was calibrated by the Au^{198}, Cs^{137}, and Bi^{207} internal conversion peaks of energies 328.7, 624.6, and 974 kev, respectively. The pulses from the anthracene detector were discriminated at 1 v. From Fig. 1

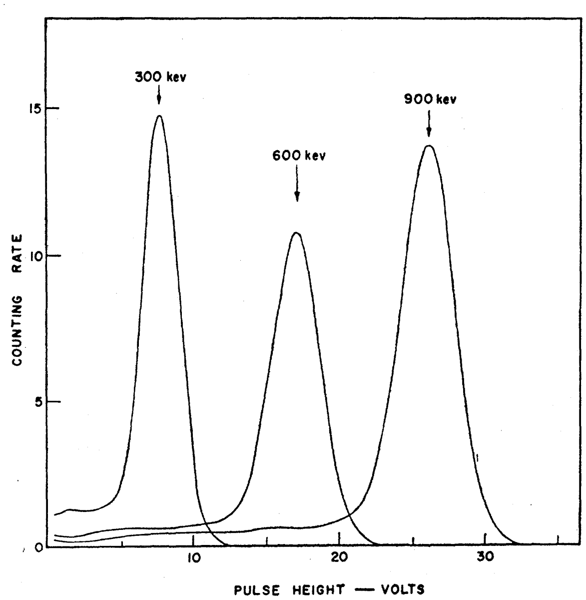

FIG. 2. Pulse height distribution in anthracene detector above 0.5 volt, with electrons of different energies focussed on it.

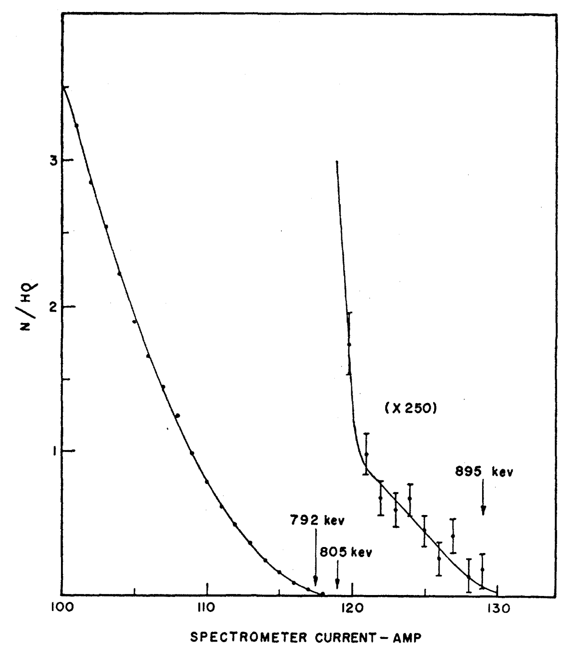

FIG. 3. Beta spectrum of Nd^{147} in the energy region above 600 kev.

it is estimated that the detector response is better than 99.5% for electron energies above 300 kev. Since the maximum pulse height was not too large even for 1-Mev electrons, the influence of afterpulses was considered negligible. The spectrum was recorded over a period of 5 hr and the data were corrected for the source decay and finite resolution of the spectrometer. The theoretical spectrum of suitable end-point energy was distorted for the finite resolution of the spectrometer according to the shape of the conversion line of Cs^{137}. The correction factors at each momentum setting were directly obtained by comparing the theoretical spectrum with the distorted one. Also the observed shapes of the conversion lines of the calibration sources were alike in the energy region of interest.

The Fermi plot of the beta spectrum observed in the above manner for Au^{198} is shown in Fig. 4. The correction factor, $C(W)=n/[p^2F(W_0-W)^2]$, is plotted in Fig. 5 for two different values of W_0. The curve for $W_0=1466$ kev does not show any slope while the curve for $W_0=1468$ kev shows a slope of about 2% over the energy range of 400 to 900 kev. The value of W_0 could be in error of ±5 kev and these observations agree fairly well with other measurements.[10]

The spectrum of Nd^{147} was recorded in a similar manner. The source was prepared from an enriched, irradiated, and purified sample of Nd^{146}. The source thickness was measured by comparison method to be 1.8 mg/cm². The spectra were recorded over a period of 5 hr and four such spectra taken on consecutive days were integrated at each ampere point, after being normalized for the source decay. The data were further corrected for the decay during each single measurement and for the finite resolution of the spectrometer in a manner described earlier. It may perhaps be mentioned that the influence of source thickness (1.8 mg/cm²) will be to reduce the effective end-point energy by about 2 kev. The contribution due to scattering in the source volume in the above energy region will be very low. The observations were also compared by using carrier-free purified neodymium sources from fission products. Here much thinner sources were prepared in the above manner and the spectrum was also repeated over four half-lives. No significant difference in the shape, as described above, has been observed.

The Fermi curve obtained from the processed data is shown in Fig. 6. It is seen that the curve is not a straight line in the energy region of 500 to 800 kev.

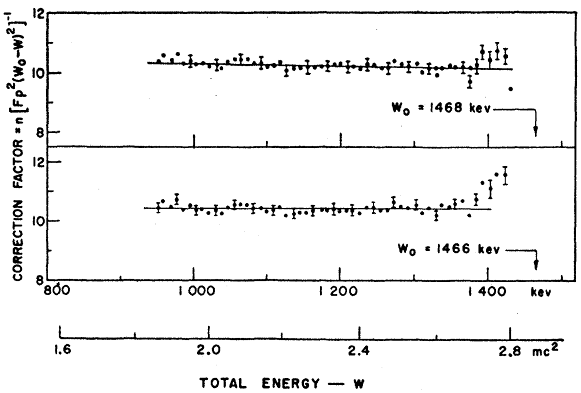

FIG. 5. Shape correction factor $C(W)$ for Au^{198} spectrum with two different values of W_0.

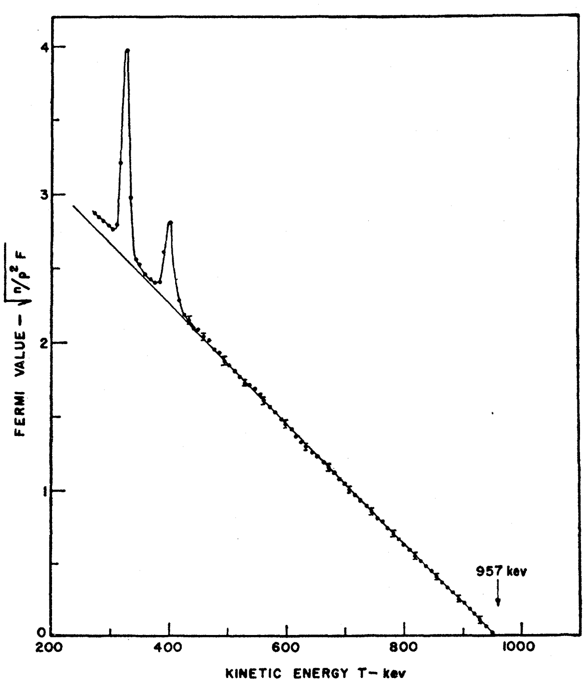

FIG. 4. Fermi plot of the beta spectrum of Au^{198}.

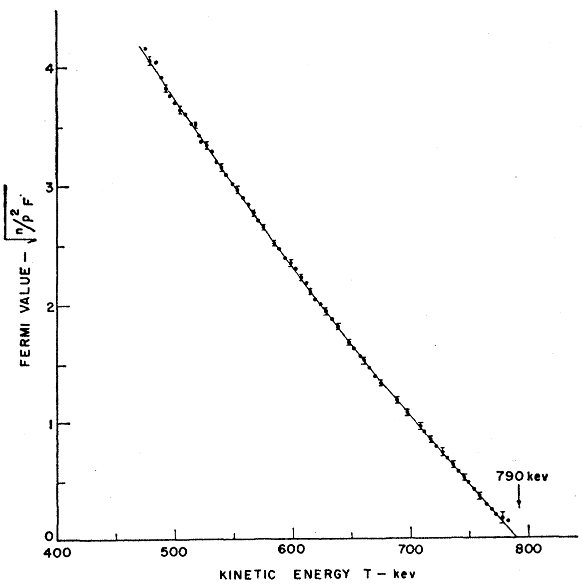

FIG. 6. Fermi plot of the beta spectrum of Nd^{147}.

[10] P. T. Porter, M. S. Freedman, T. B. Novey, and F. Wagner, Jr., Phys. Rev. 103, 921 (1956).

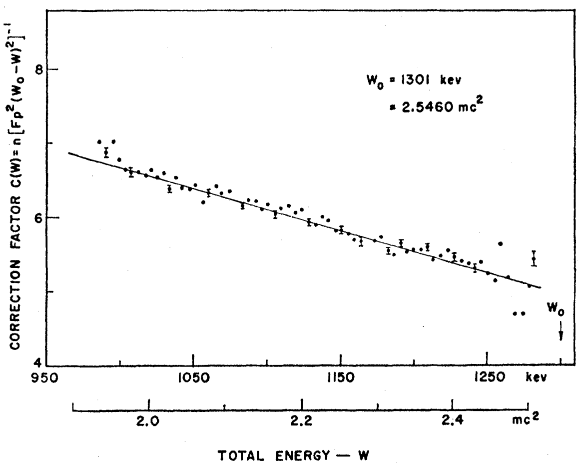

FIG. 7. Shape correction factor for the beta spectrum of Nd^{147}.

Since there is no evidence[5,9] for the presence of any intermediate level between 90 and 410 kev, the deviation from the straight-line nature of the Fermi curve should be regarded as a deviation from statistical shape. The shape correction factor of these measurements is shown in Fig. 7. The value of W_0 for these data is so chosen that the correction curve is neither concave towards the energy axis[11] nor there is a large sudden upward trend of the points near the end-point energy.

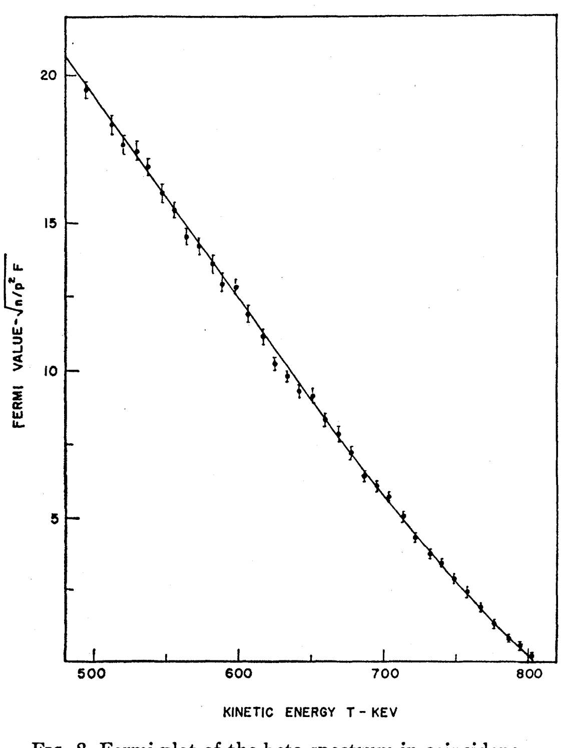

FIG. 8. Fermi plot of the beta spectrum in coincidence with 91-kev gamma ray.

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The above observations of the nonstatistical shape of beta transition feeding the 91-kev level was further confirmed by studying the beta spectrum in coincidence with 91-kev gamma ray. This gamma ray was detected in a 1.5-in. diam×1 in. thick NaI(Tl) crystal placed at a distance of 3 cm behind the source and coupled to a photomultiplier tube through a light guide. A standard fast-slow coincidence circuit of resolving time $2\tau = 0.1$ μsec was used to study the coincidences. In order to improve the coincidence counting rate, the magnetic spectrometer transmission was increased to about 8% with a corresponding loss in resolution to 4.5%. The performance of the coincidence set up was also checked by studying the Au^{198} beta spectrum in coincidence with the 412-kev gamma ray. The Fermi curve of the coincidence spectrum of Nd^{147} corrected for the decay and finite resolution of the spectrometer is shown in Fig. 8. It is seen that the Fermi curve is essentially of the same form as in Fig. 6. The corresponding values of the correction factor obtained by taking a suitable end point is given in Fig. 9. The nature of this curve confirms the results obtained from measurements on singles spectrum. It should be mentioned that the difference in the end-point energy used for the representation of the data in Fig. 6 and Fig. 8 is due to two independent measurements with different pole pieces for the spectrometer having a calibration error of about 1%.

Beta Transition to the 531-kev Level

The intensity of the beta transition feeding the 531-kev level is about 16%. The beta spectrum in coincidence with the 531-kev gamma ray was observed with the same arrangement as described above. However, the NaI(Tl) crystal was directly coupled to the photomultiplier tube without a light guide. The tube was protected from the magnetic field by a mu-metal shield. There was no observable shift in the pulse height of the 531-kev gamma ray when the magnetic spectrometer current was varied in the energy region

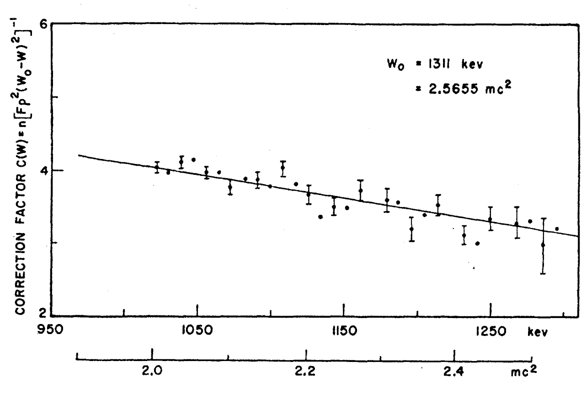

FIG. 9. Shape correction factor for the beta spectrum in coincidence with the 91-kev gamma ray.

of 200 to 400 kev. The resolution of the gamma-ray scintillation spectrometer was 10% for the 660-kev gamma-ray. The resolving time of the circuit was reduced to $2\tau=0.03$ μsec to improve the true-to-chance coincidence ratio, particularly near the end point of the beta spectrum.

In studying the coincidence beta spectrum with the 531-kev gamma ray there is a possibility of observing the beta component of end-point energy 395 kev feeding the 487-kev level, because of the presence of the 487-kev gamma ray[9] which could be detected in the 531-kev gamma-ray channel. To suppress its contribution, the gamma channel was fixed in the energy region of 530 to 590 kev. In doing so, the 585-kev gamma ray emitted from the 686-kev level was also detected in the gamma channel. This gamma ray is in coincidence with the beta group of end-point energy 195 kev. Hence the measurements were limited in the energy region above 200 kev. The coincidence spectrum was repeatedly recorded, four times, under identical circumstances and the number of counts at each momentum setting was integrated. The Fermi curve of the coincidence spectrum corrected for the finite resolution of the spectrometer is shown in Fig. 10. It is seen that the points follow the straight-line curve. The statistical shape of the spectrum is further confirmed by plotting the correction factor $C(W)$ calculated for an end-point energy 360 kev, which is shown in Fig. 11. This value of the end-point energy for the beta group feeding the 531-kev level is consistent with the corresponding value

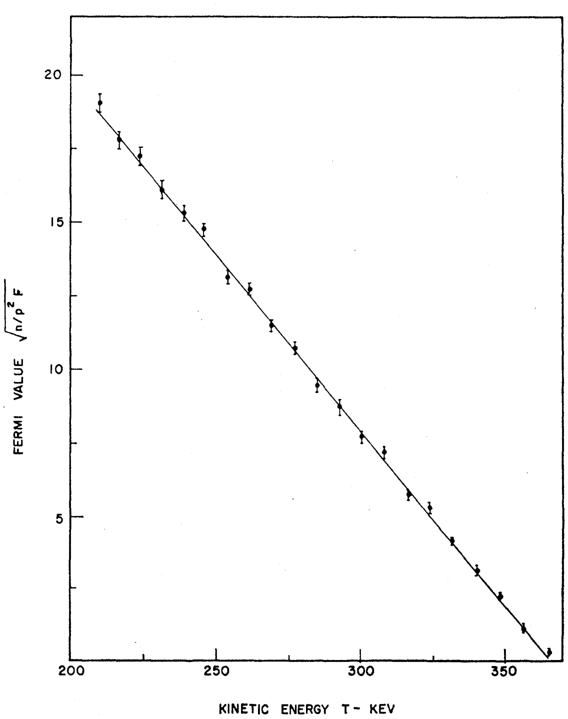

FIG. 10. Fermi plot of the beta spectrum in coincidence with the 531-kev gamma ray.

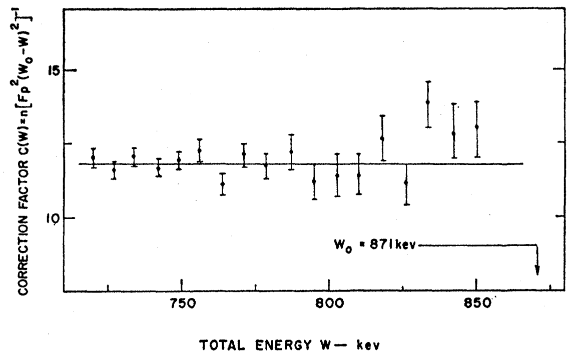

FIG. 11. Shape correction factor for the beta spectrum in coincidence with the 531-kev gamma ray.

of 800 kev for the beta group feeding the 91-kev level, as measured by the spectrometer with same pole pieces. It is observed that within the experimental uncertainties, $C(W)$ remains constant over a large region of energy. A little larger value of $C(W)$ near the end-point energy may be due to a partial detection of the 487-kev gamma ray. It is, therefore, concluded that the 360-kev beta group feeding the 531-kev level is predominantly statistical in shape.

DISCUSSION

According to the shell model, the neutrons outside the closed shell at neutron number 82, could go in $h_{9/2}$ or $f_{7/2}$ subshells. The spins of Nd^{143}, Nd^{145}, Sm^{147}, and Sm^{149} having 1, 3, 3, and 5 neutrons outside the closed shell, respectively, are all measured[11] as $\frac{7}{2}$. However, the measured spin of Nd^{147} is $\frac{5}{2}$, and the five neutrons in this nucleus presumably form a configuration state of spin $\frac{5}{2}$ with five neutrons in $f_{7/2}$ state. On the other hand, the ground and 91-kev excited states of Pm^{147} having spin values of $\frac{7}{2}$ and $\frac{5}{2}$, respectively, could be pure $g_{7/2}$ and $d_{5/2}$ single-particle states.

The log *ft* values for the beta transition to the 91-, 531-, and 686-kev excited states have normal values of 7.4, 7.0, and 6.8, respectively. These levels have been assigned the spin values $\frac{5}{2}$ from gamma-gamma angular correlation[12] and nuclear alignment studies.[13] On the other hand, the log *ft* values for the beta transitions to the 0-, 410-, and 489-kev levels are >10, 8.7, and 8, respectively. These levels have been assigned the spin values $\frac{7}{2}$, $\frac{3}{2}$ or $\frac{5}{2}$ or $\frac{7}{2}$, and $\frac{7}{2}$ or $\frac{5}{2}$, respectively. The value $\frac{5}{2}$, although possible for the two states at 410 and 487 kev from gamma-gamma angular correlation studies,[12] is very unlikely, since that would make all the five-excited states of Pm^{147} have spin $\frac{5}{2}$. Thus it is safe to conclude that the $\Delta I=1$, yes, type of transitions from Nd^{147} is comparatively retarded. The retardation factor increases with the increase of decay energy. The

[12] B. Saraf, R. Jambunathan, and M. R. Gunye, Phys. Rev. **124**, 178 (1961).

[13] G. A. Westenbarger and D. A. Shirley, Phys. Rev. **123**, 1812 (1961).

other transitions of the type $\Delta I=0$, yes, proceed normally.

From the study of the angular distribution of gamma rays from aligned nuclei Westenbarger and Shirley[13] have observed that the beta decays to the 91- 513-, and 680-kev levels are predominantly of $L=0$ type. This is in conformity with the above conclusion based on $\log ft$ values. Hence the dominant terms in the matrix element for the beta transition to the 91-kev level will be[14]

$$\eta w=C_A\int \boldsymbol{\sigma}\cdot\mathbf{r} \quad\text{and}\quad \eta\xi' v=C_A\int i\gamma_5,$$

corresponding to tensor rank $\lambda=0$.

The shape factor for such a beta transition will be akin to a $0^-\rightarrow 0^+$ transition and is given by the following expression[15]:

$$C(W)=k(1+aW+b/W),$$

where

$$k=1+(2/3)W_0[w_0(-1)/V],$$

$$ak=[2w_0(+1)/3V][1-w_0(-1)/w_0(+1)],$$

and

$$bk=-2w_0(+1)/3V.$$

The notation is that of Kotani and Ross.[15]

In the present case the measurements are essentially limited to a small energy region near the end point and the data could be fitted with a variety of values of the constants a and b over a wide range. If the contributions of the hyperbolic term b/W is considered negligible, the expression for the shape correction factor obtained by the method of least squares is $C(W)=k(1-0.23W)$. On the other hand, a least-squares-fit quadratic expression is $C(W)=-k(1+0.2W-20/W)$, in which the linear term aW is comparatively small. From the comparison of the values of these coefficients, when compared with the theoretical expressions, it is seen that $w_0(-1)/V=0.85$ and $w_0(+1)=0$ in the first case and $w_0(-1)/V\approx w_0(+1)/V\approx -0.6$ in the second case.

If, in this beta transition, the total angular momentum transfer to the electron-neutrino system is predominantly zero, the beta-gamma angular correlation will be isotropic, corresponding to the transition matrix elements of tensor rank $\lambda=1$ and 2 being zero.[16] Hence the measurement of the beta-gamma angular correlation is desirable to substantiate or reject the above conclusions. The measurement of longitudinal polarization of the beta particles will be able to differentiate the predominance of the linear term aW or the hyperbolic term b/W in the shape correction factor.

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[14] G. E. Bradley, F. M. Pipkin, and R. E. Simpson, Phys. Rev. **123**, 1824 (1961).

[15] T. Kotani and M. H. Ross, Progr. Theoret. Phys. (Kyoto) **20**, 643 (1958).

[16] T. Kotani, Phys. Rev. **114**, 795 (1959).