been suggested by us[1] (and independently by Daunt and Heer[11]) to make use of the change of heat conduction in superconductors for make and break thermal contacts at very low temperatures. The present results show that in order to get a great difference of heat flow in the two states very pure metals should be used. On the other hand, it now seems to be possible to design thermal switches which ***break*** a contact on magnetization by employing an alloy.

[11] C. V. Heer and J. G. Daunt, Phys. Rev. **76**, 854 (1949).

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The Disintegration of Praseodymium 142

ERLING N. JENSEN, L. JACKSON LASLETT, AND D. J. ZAFFARANO
*Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa**

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The radiations from Pr^{142} have been examined with a thin lens spectrometer. One gamma-ray was found having an energy of 1.57_6 Mev. The beta-spectrum is complex, the two groups observed having maximum kinetic energies of 2.15_4 Mev and 0.63_6 Mev. It is suggested that the high energy beta-group gives a transition to the ground state of Nd^{142} and that the gamma-ray follows the low energy beta-transition. The half-life was found to be 19.1 hr. The electron distribution produced by bremsstrahlung, due to the absorption of the beta-rays, was observed.

I. INTRODUCTION

THE characteristic radiations of Pr^{142} were investigated by Amaldi[1] and others, but in more detail recently by absorption and coincidence methods by Bothe,[2] Mandeville,[3] and Jurney.[4] Data obtained with spectrometers have been reported by DeWire *et al.*,[5] Peacock *et al.*,[6] Cork *et al.*,[7] and Rae.[8]

The radiations found by these authors are shown in Table I.

The coincidence work of Mandeville and Jurney has established that the 1.6-Mev gamma-ray probably follows the soft beta-transition, while the higher energy beta results from a disintegration to the ground state of Nd^{142}. Delayed coincidence work by DeBenedetti and and McGowan[9] showed that there are no metastable states in Nd^{142} with half-lives in the range 10^{-6} to 10^{-3} sec.

DeWire *et al.*[5] remark that the higher energy beta-ray arises from a first-forbidden transition, according to Konopinski's notation,[10] and a characteristic "forbidden shape" is suggested by their Kurie plot. The fact that Nd^{142} is a "magic number" nucleus in neutrons, and the somewhat conflicting evidence for the decay scheme of Pr^{142} led the authors to the present study.

Two 100-mg samples of spectrographically pure (contaminants less than 0.1 percent) Pr_6O_{11} (empirical formula) made available through the courtesy of Dr. F. H. Spedding and Mr. T. A. Butler of this laboratory were bombarded in the Oak Ridge pile and then examined with a thin-lens spectrometer[11] modified to incorporate ring focusing.[12]

II. HALF-LIFE

The half-life of Pr^{142} was determined by following the activity of a sample of $PrCl_3$ with a Lauritsen electroscope for more than four half-lives. A value of 19.1 hr. was obtained. This is in good agreement with the values reported by Bothe[2] (19.2 hr.) and DeWire, Pool, and Kurbatov[5] (19.3 hr.).

III. SECONDARY ELECTRON SPECTRUM

The spectrometer was calibrated by means of the F conversion line of ThB (1385 $H\rho$). All the data reported in this paper were obtained with a spectrometer resolution of 2.1 percent (half-width) and a Geiger counter window of Formvar with a cut-off at 15 kev. The data have not been corrected for window absorption.

Since praseodymium has a single isotope,[13] namely Pr^{141}, it is assumed that only the radiations of Pr^{142} were observed in this investigation.

To obtain the secondary electron spectrum, the Pr^{142} was placed in a Lucite holder and covered with a copper cap, of surface density 1.4 g/cm², in order to absorb the

* Contribution No. 112 from the Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa. Work was performed in the Ames Laboratory of the AEC.

[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. **149A**, 522 (1935).
[2] W. Bothe, Zeits. f. Naturforsch. **1a**, 173 (1946).
[3] C. E. Mandeville, Phys. Rev. **75**, 1287 (1949).
[4] E. T. Jurney, Phys. Rev. **76**, 290 (1949).
[5] DeWire, Pool, and Kurbatov, Phys. Rev. **61**, 544 (1942); Phys. Rev. **61**, 564 (1942).
[6] Peacock, Jones, and Overman, PPR Mon N-432 (1947).
[7] Cork, Schreffler, and Fowler, Phys. Rev. **74**, 1657 (1948).
[8] E. R. Rae, Proc. Phys. Soc. (London), **63A**, 292 (1950).
[9] S. DeBenedetti and F. K. McGowan, Phys. Rev. **74**, 728 (1948).
[10] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
[11] Jensen, Laslett, and Pratt, Phys. Rev. **75**, 458 (1949).
[12] Pratt, Boley, and Nichols, Phys. Rev. **79**, 208 (1950); Keller, Koenigsberg, and Paskin, Phys. Rev. **76**, 454 (1949).
[13] Inghram, Hess, and Hayden, Phys. Rev. **74**, 98 (1948).

beta-particles. On the copper cap was fastened a uranium foil having a surface density of 42 mg/cm^2. This source was placed in the spectrometer about 19 hours after the sample was removed from the Oak Ridge pile. The spectrum obtained is shown in Fig. 1. The insert in Fig. 1 shows the arrangement of the source of Pr^{142}, Lucite holder, copper cap, and uranium foil.

The K and L photo-electron lines of a single gamma-ray were observed. The mean value of the weighted gamma-ray energies, as determined from the K and L lines, was found to be 1.57_6 Mev. In calculating the gamma-ray energy a correction was made for the surface density of the uranium foil.[11] A search was made for low energy gamma-rays, using an Ag foil as a radiator, but none was found.

The broad distribution of electrons, exhibiting a maximum intensity at 1800 gauss-cm (Fig. 1), resembles the Compton distribution of a single gamma-ray but is not accompanied by the photoelectric conversion lines which would be expected to be associated with such a distribution. A search for weak photo-electron lines was made with a second sample of Pr^{142}, but none was found. The broad electron distribution, which shows the same decay constant as the remainder of the spectrum, is, accordingly, attributed to secondary electrons produced by bremsstrahlung arising from the passage of the beta-rays through the source-material and into the copper cap. An approximate calculation was made of the Compton electron distribution which would arise in a thick radiator from the bremsstrahlung expected[14] to originate in copper traversed by electrons possessing an energy distribution similar to those of the Pr^{142} beta-rays. The computed distribution resembled closely, in magnitude and in shape throughout the region of major interest, the extended distribution observed.

As a check of the foregoing interpretation for the prominent broad electron distribution observed, a source of $Sr^{90}-Y^{90}$ was placed in the spectrometer and covered with the same copper cap and uranium radiator

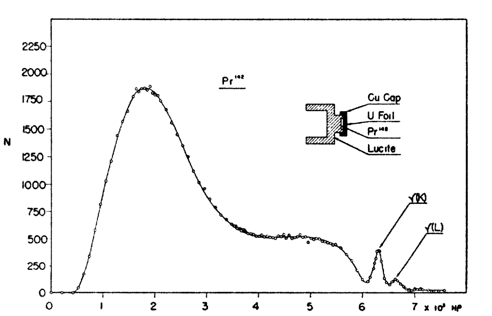

FIG. 1. Secondary electron distribution produced by Pr^{142}, from a copper cap (1.4 g/cm^2) and a uranium foil (42 mg/cm^2). The insert shows the Lucite holder, Pr^{142}, copper cap, and uranium foil. N is the observed counting rate. This diagram shows the electron distributions produced by bremsstrahlung, Compton scattering and the photoelectric effect.

[14] W. Heitler, *The Quantum Theory of Radiation* (Oxford Univeristy Press, New York, 1944), Ed. 2, p. 161.

TABLE I. Radiations from Pr^{142} reported by previous investigators.

Authors	β (Mev)	γ (Mev)
Mandeville	2.22, 0.215	1.74, 0.17
Jurney	2.52, 0.350	1.53
Cork *et al.*		0.62, 0.49, 0.33, 0.13 (from internal conversion lines)
DeWire *et al.*	2.14	1.9
Peacock *et al.*	2.23	$\sim$1.65, $\sim$1.3
Rae	2.23, 0.66	1.59, 0.14 (I.C.).

used in the work with Pr^{142}. The strontium-yttrium source, which is gamma-free and emits beta-particles with a maximum energy[15] (2.23 Mev) close to that for Pr^{142}, was found to give under these conditions a secondary electron distribution (Fig. 2) of the type which we have attributed to bremsstrahlung in the case of Pr^{142}. The spectrum shown in Fig. 1 is thus regarded as a *composite* of the photoelectrons and Compton electrons arising from a single gamma-ray plus the electrons produced by bremsstrahlung. The contribution of bremsstrahlung to the secondary electron spectrum is especially prominent in the case of Pr^{142}, since there are about 25 beta-particles per gamma-ray (see Section V).

IV. BETA-RAY SPECTRUM

The beta-ray source was prepared by dissolving a portion of the irradiated Pr_6O_{11} in dilute HCl. A drop of the solution was deposited on a Formvar-polystyrene film, of surface density about 40 μg/cm^2, and allowed to evaporate to dryness. The average surface density of the source was about 1.1 mg/cm^2. The source was grounded by means of the technique described by Langer.[16] The beta-spectrum obtained is shown by the solid line in Fig. 3. The beta-spectrum determined with an earlier source revealed no internal conversion lines between the counter window cut-off and about 1100 gauss-cm. If the internal conversion lines reported by Cork *et al.*[7] actually exist, we estimate that the height of the lines is less than five percent of the counting rate at the corresponding positions of the beta-spectrum.

The allowed Kurie plot did not yield a straight line, but gave a curve characteristic of a first-forbidden transition (Gamow-Teller selection rules), with a spin change of two units and a parity change. The allowed Kurie plot is shown in Fig. 4. The modified Kurie plot with the approximate correction factor $a=(W_0-W)^2+W^2-1$, which has been considered appropriate for a spin change of two units with a parity change,[10] is shown by the crosses in Fig. 5. This curve indicates the presence of two beta-groups. The maximum kinetic energy of the high energy group is 2.15 Mev. On subtracting the high energy group, estimated in this way, from the total distribution, the maximum kinetic energy of the low energy group, as determined from the Kurie plot, was about 1.1 Mev. The difference between these

[15] E. N. Jensen and L. J. Laslett, Phys. Rev. **75**, 1949 (1949).
[16] L. M. Langer, Rev. Sci. Inst. **20**, 216 (1949).

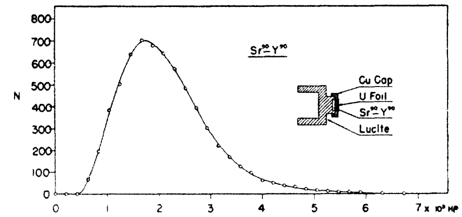

FIG. 2. Secondary electron distribution produced by a pure beta-source of $Sr^{90}-Y^{90}$, from a copper cap (1.4 g/cm^2) and a uranium foil (42 mg/cm^2). The electron distribution is produced by the bremsstrahlung formed in the copper cap due to the absorption of the beta-rays from $Sr^{90}-Y^{90}$.

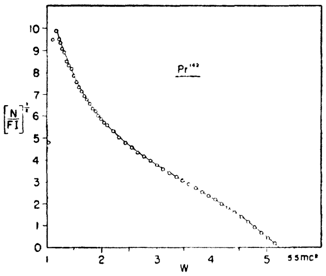

FIG. 4. The allowed Kurie plot of the beta-spectrum of Pr^{142}.

two beta-energies is *not* in good agreement with the gamma-ray energy of 1.57_6 Mev.

The work of Marshak[17] and Greuling[18] suggests that a more precise form for the correction factor would be $a=(W_0-W)^2+\Lambda(W^2-1)$, where the coefficient Λ is not strictly independent of the electron momentum and differs appreciably from unity when Z is large. A graph showing Λ as a function of electron momentum for $Z=40$ and $Z=60$, which is appropriate for Pr, has been published recently.[19] In the case of Pr^{142} the coefficient Λ makes an appreciable difference in the modified Kurie plot, as is shown by the circles in Fig. 5. This plot gives a maximum kinetic energy of 2.15_4 Mev. An additional indication of the improvement obtained by including the coefficient Λ is given by the r.m.s. weighted relative differences between the straight line modified Kurie plots and the individual observed counting rates. Including all points with W greater than 2.3 mc^2, these values are 2.5 percent with $\Lambda=1$ and 0.8 percent with Λ as given by Fig. 1 of reference 19.

In subtracting the high energy beta-group and making a Kurie plot of the low energy beta-group, the data were not sufficiently accurate to determine whether or not this beta-group is of the allowed form. The allowed Kurie plot of this low energy group is shown in Fig. 5. The maximum kinetic energy is 0.63_6 Mev. This energy is in fairly good agreement with the maximum energy of the high energy beta-group and the energy of the gamma-ray. The agreement is much better if a modified Kurie plot is made using the correction factor, a. This gives a maximum kinetic energy of 0.58_1 Mev. However, for reasons discussed in Section V, it is believed that the low energy beta-group is probably a first-forbidden transition, but is *not* of the type in which the correction factor is appropriate.

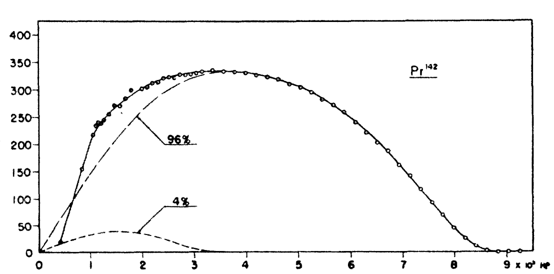

FIG. 3. Beta-spectra of Pr^{142}. The solid curve is the observed spectrum while the dashed curves represent the two beta-groups, calculated from the respective Kurie plots. N is the observed counting rate and I is the current in the spectrometer coil.

There are two primary sources of error in the low energy beta-group. One is the low intensity of the group together with the additional error introduced by subtraction of the high energy group. The second error involves a small apparent loss of the source while in the spectrometer. The mean half-life determined from points taken at different times at 20 different current values was found to be 18.4 hr. This is appreciably lower than that reported in Section II. It is believed that the vacuum in the spectrometer is sufficient to remove some of the water of hydration of the $PrCl_3$, which in turn may result in the removal of a small amount of the $PrCl_3$. This would explain the smaller half-life obtained from the spectrometer data. The importance of this effect was minimized by repeated traversals of the spectrum, which led to consistency in the data when a correction was applied for the observed half-life.

The deviations from the straight line of the points below $W=1.55$ mc^2 is thought to be due to the fairly large surface density of the source.

V. DISCUSSION

A consistent decay scheme for Pr^{142} is shown in Fig. 6. Since Nd^{142} is an even-even nucleus, it is reasonable to assume that the ground state has a spin of zero and even parity. The high energy beta-group is first forbidden with a spin change of two units and a parity change. Hence the ground state of Pr^{142} is assigned a spin of two units with odd parity. This is in complete agreement with the predictions of the nuclear shell model[20] in regard to parity, and to spin in accordance with rule nine proposed by Nordheim[21] for the case of beta-decay for odd-odd nuclei.

Although the Kurie plot with the correction factor gave a suitable straight line and a maximum energy for the soft beta in excellent agreement with the difference

[17] R. E. Marshak, Phys. Rev. **61**, 431 (1942).
[18] E. Greuling, Phys. Rev. **61**, 568 (1942).
[19] Laslett, Jensen, and Paskin, Phys. Rev. **79**, 412 (1950).
[20] M. G. Mayer, Phys. Rev. **78**, 16 (1950).
[21] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).

between the high energy beta-group and the gamma-ray, it appears to be very unlikely that the transition is one with a spin change of two units and a parity change. This would demand a spin of zero or four units with even parity for the 1.57-Mev level. A gamma-ray transition between two states with $I=0$ is strictly forbidden. A gamma-ray transition of 1.57 Mev with a spin change of four units and no change of parity would require a

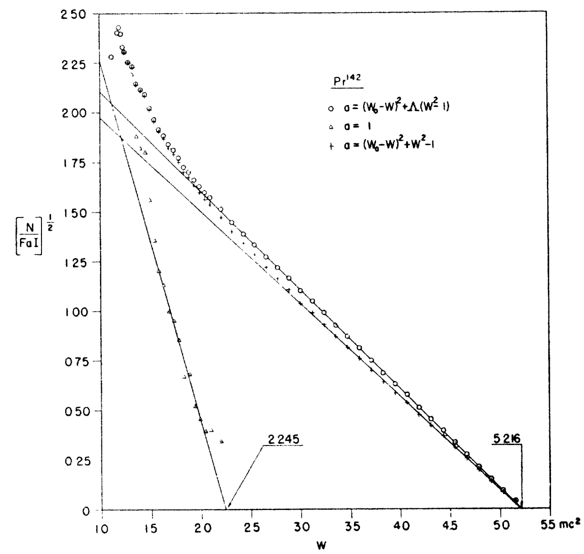

FIG. 5. The modified Kurie plots of Pr^{142}. The low energy group was obtained by the usual subtraction.

metastable state with a half-life[22] of 3.2×10^{-6} sec. DeBenedetti and McGowan[9] report a negative result of a search for a metastable state of Nd^{142} in the range 10^{-6} to 10^{-3} sec. The *ft* value of the low energy group is 9×10^{6}, which is classed empirically as first forbidden.[10] According to selection rules this demands a change in parity, hence the 1.57 Mev level is assigned an even

[22] E. Segrè and A. C. Helmholz, Rev. Mod. Phys. **21**, 271 (1949).

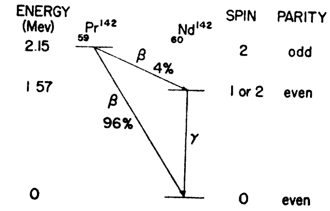

FIG. 6. Decay scheme of Pr^{142}.

parity. The gamma-ray transition then involves no change in parity. The possible spin assignments of the 1.57-Mev level are 1 or 2 units. For a spin of 1 unit the gamma-radiation is either magnetic dipole or a mixture of magnetic dipole and electric quadrupole. For a spin of 2 units the gamma-radiation is electric quadrupole. This gives a spin change of one or zero units for the low energy beta-transition.

The high energy beta-group has an *ft* value of 0.6×10^{8}, which is in agreement with the values of *ft* given by Nordheim[21] in rule number six for this type of transition. The (W_0^2-1) *ft* value for this group is 0.2×10^{10} which also is in good agreement with the values given by Shull and Feenberg[23] for several other nuclei undergoing beta-transitions of a similar character, in which the spin change is two units with a parity change.

Assuming that the high energy group is first forbidden with a spin change of two units and a parity change, and the low energy group to be represented by an "allowed" Kurie plot the percentage transitions associated with these groups are 96 and 4, respectively. These two beta-groups are shown by the dashed curves in Fig. 3.

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[23] F. B. Shull and E. Feenberg, Phys. Rev. **75**, 1768 (1949).