TABLE IV. Distance $d=(K_i-K_f)/-\langle\partial E/\partial x\rangle_{Av}$ is that traveled in lead when a particle of mass $200m_\epsilon$ and of an initial kinetic energy K_i loses by ionization an amount of energy equal to K_i-K_f, where K_f is the kinetic energy which the particle possesses after having traversed d. The average ionization loss per cm $-\langle\partial E/\partial x\rangle_{Av}$ is read from the curves in Fig. 3. The sum of the d's gives the range for a given K_i.

K_i (in ev)	K_f (in ev)	Av. $-(\partial E/\partial x)_{Av}$ (in ev/cm)	d (in cm)	Range (in cm)
10^4	0	10^{10}	10^{-6}	10^{-6}
10^5	10^4	5.0×10^8	1.8×10^{-5}	$10^{-6}+1.8\times10^{-5}=1.9\times10^{-5}$
5×10^5	10^5	5.0×10^8	10^{-3}	1.02×10^{-3}
10^6	5×10^5	2.7×10^8	1.85×10^{-3}	2.87×10^{-3}
5×10^6	10^6	1.14×10^8	3.54×10^{-2}	3.83×10^{-2}
10^7	5×10^6	5.85×10^7	8.55×10^{-2}	0.125
2×10^7	10^7	3.41×10^7	0.294	0.419
—	—	—	—	—

mass M, where $\langle\alpha_1^2\rangle_{Av}+\langle\alpha_2^2\rangle_{Av}=\langle\theta^2\rangle_{Av}$ and θ is the total scattering angle, and α_1 and α_2 are the scattering angles projected in two perpendicular planes, each of which contains the track of the incident particle. Neglecting the energy loss by ionization in the scattering material, taking into consideration shielding by electrons, and using a finite nucleus with a radius of 10^{-12} cm, Williams obtains the following expression:

$$(\langle\alpha_1^2\rangle_{Av})^{\frac{1}{2}}=\left(\frac{\pi}{2}\right)^{\frac{1}{2}}[19.5-3.1\log_{10}Z]^{\frac{1}{2}}\frac{2(Nt)^{\frac{1}{2}}Ze^2(1-\beta^2)^{\frac{1}{2}}}{Mc^2\beta^2},$$

where W is the atomic weight, Z is the atomic number, t is the thickness, and N is the number of atoms per cc of the scattering material, and e is the electronic charge. The values of $(\langle\alpha_1^2\rangle_{Av})^{\frac{1}{2}}$ *vs.* the kinetic energy for both mesotrons and protons are plotted in Fig. 1.

It is now desired to calculate the corresponding values of $(\langle\alpha_1^2\rangle_{Av})^{\frac{1}{2}}$ when the energy loss in the plate is taken into account. Consider a particle of mass $200m_\epsilon$ entering the 1.3-cm lead plate with a kinetic energy of 8×10^7 ev. It will be seen from curve 5 of Fig. 3 that this particle will emerge with a kinetic energy of 6.1×10^7 ev. For the average between the energies 8×10^7 and 6.1×10^7 ev, the scattering angle $(\langle\alpha_1^2\rangle_{Av})^{\frac{1}{2}}$ was read from the curve in Fig. 2. If this value of $(\langle\alpha_1^2\rangle_{Av})^{\frac{1}{2}}$ is now plotted against the incident kinetic energy of 8×10^7, we obtain a point on the curve for $(\langle\alpha_1^2\rangle_{Av}{}^1)^{\frac{1}{2}}$. For lower kinetic energies the averaging process was made more precise by dividing the plate up into thin sections, numbered a, b, c, $\cdots$, and calculating the average kinetic energy of the particle in each section and in turn the resulting $(\langle\alpha_1^2\rangle_{Av}{}^1)^{\frac{1}{2}}$ in each section. The total $(\langle\alpha_1^2\rangle_{Av}{}^1)^{\frac{1}{2}}$ for the 1.3 cm of lead is given by

$$(\langle\alpha_1^2\rangle_{Av}{}^1)^{\frac{1}{2}}=[\langle\alpha_a^2\rangle_{Av}+\langle\alpha_b^2\rangle_{Av}+\langle\alpha_c^2\rangle_{Av}+\cdots]^{\frac{1}{2}}.$$

MAY 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 61

Radioactive Isotopes of Praseodymium

J. W. DEWIRE,* M. L. POOL, AND J. D. KURBATOV
The Ohio State University, Columbus, Ohio

(Received March 3, 1942)

New nuclear reactions $Pr^{141}(dp)$, $Ce^{142}(pn)$, and $La^{139}(\alpha n)$ yielding radioactive isotope Pr^{142} have been observed. The decay curves obtained for Pr^{142} after chemical purifications showed a half-life of 19.3 ± 0.1 hours, a value considered to be more exact than that previously reported. The negative beta-ray spectrum was measured with a recently constructed magnetic spectrometer of the 180° focusing type and was found to have an end point of 2.14 ± 0.02 Mev. A weak gamma-ray approximately 1.9 Mev was found associated with this period. The isotope Pr^{140} has been formed by the reaction: $Pr^{141}(n,2n)$. Its half-life was measured as 3.4 ± 0.1 minutes. Cloud-chamber measurements yield an upper limit of 2.40 ± 0.15 Mev for its positron spectrum.

I. INTRODUCTION

THE study of radioactivity in praseodymium began with the work of Fermi and coworkers, who produced periods of 5 minutes and 19 hours by bombarding praseodymium with neutrons.[1] They reported that the 19-hour period was sensitive to water and found a half-value thickness for its beta-rays of 0.12 g/cm² of aluminum. Marsh and Sugden[2] assigned the 19-hour period to Pr^{142}, and Pool and Quill[3] found that the shorter period was a 3.5-minute positron emitter and assigned it to Pr^{140}. Recently these assignments were confirmed by Wu and Segrè,[4] who reported that the half-life of Pr^{142} was 18.7 hours. They found that this isotope emitted only electrons with a continuous spectrum having an upper limit of 2 Mev.

* Now at Princeton University, Princeton, New Jersey.
[1] E. Fermi *et al.*, Proc. Roy. Soc. **149**, 522 (1935).
[2] J. K. Marsh and S. Sugden, Nature **136**, 102 (1935).
[3] M. L. Pool and L. L. Quill, Phys. Rev. **53**, 437 (1938).
[4] C. S. Wu and E. Segrè, Phys. Rev. **61**, 203 (1942).

In this study, other possible methods of formation of these two isotopes have been investigated. The electron spectrum of Pr^{142} has been measured by a magnetic spectrometer, the positron spectrum of Pr^{140} by a Wilson cloud chamber. A weak gamma-ray has been found associated with Pr^{142}; its energy has been measured by absorption in lead.

II. THE 19.3-HOUR PERIOD

A. Formation and Half-Life

Figure 1 shows an isotopic chart of the region studied. The stable isotopes are represented by rectangles, the unstable isotopes by ovals. The reactions which were studied in this work are shown by the heavy arrows. The values found for the radiations from Pr^{140} and Pr^{142} are given in heavy print.

The 19.3-hour period was formed by the action of deuterons and neutrons on praseodymium, protons on cerium, and alpha-particles on lanthanum. Hilger H.S. brand oxides were used in all the bombardments. A spectroscopic study, delivered by Hilger, revealed the following impurities in these materials:

Praseodymium oxide, Lab. No. 6782—Mg, 0.1 percent; Dy, 0.02 percent.

Cerium oxide, Lab. No. 6401—traces of Mg and Gd.

Lanthanum oxide, Lab. No. 6404—very slight traces of Na, Mg, Ca, Bi, Sm; Gd, 0.015 percent; Nd, 0.1 percent.

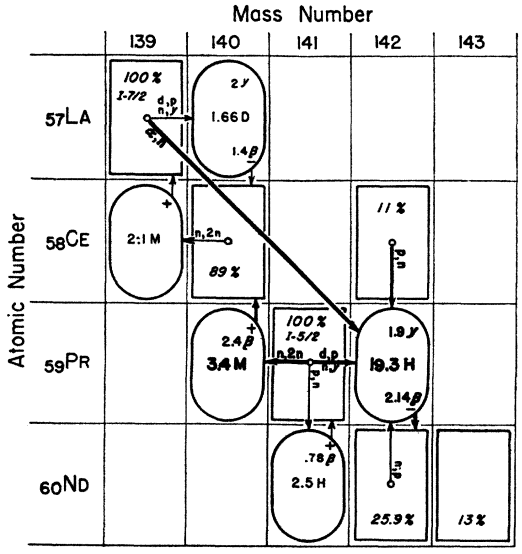

FIG. 1. Isotopic chart of praseodymium region.

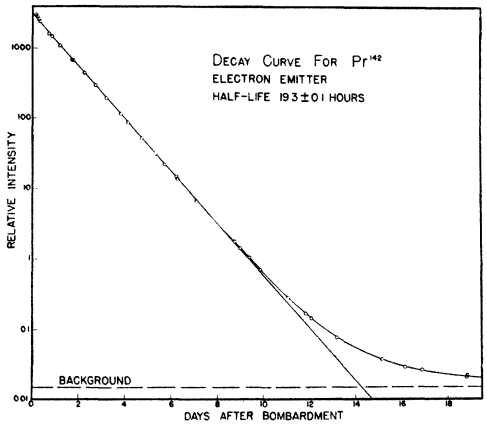

FIG. 2. Decay curve for Pr+*d*.

A study of the distribution of the stable isotopes in the praseodymium region leads to the conclusion that the reactions forming the 19.3-hour period assign the period to Pr^{142}. The chemical procedures of purification were arranged to remove all active impurities other than the rare earths, which might originate either from the target material or the bombarded sample. The same procedures were followed in all the bombardments leading to the 19.3-hour period. The bombarded sample was first dissolved in nitric acid and evaporated to dryness, the process being repeated several times to drive off all volatile active substances. Then the residue was again dissolved in nitric acid and filtered to remove any insoluble activity from the platinum target. After filtration, carriers were added, such as Cu, Ni, Co, Na, K, Cs, Ca, Ba, and Sr. The filtrate was then neutralized with ammonium hydroxide added in excess. This precipitated the rare earths and left the above shown impurities in solution. The rare-earths' precipitate was filtered, and afterward was redissolved in nitric acid. Other carriers such as Fe, Al, Cr, Ti, etc., were added, and the rare earths were precipitated by oxalic acid and filtered off. In case any of the filtrates showed activity when measured with an immersion type G-M tube, carriers were again added and the rare earths precipitated once more. The oxalates of the rare earths were finally converted to the oxides, whose activity was followed.

The activities were measured by an ionization chamber containing Freon at a pressure of two

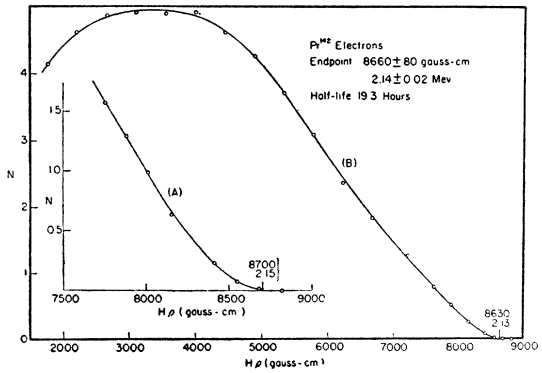

FIG. 3. Momentum distribution of the Pr^{142} electrons.

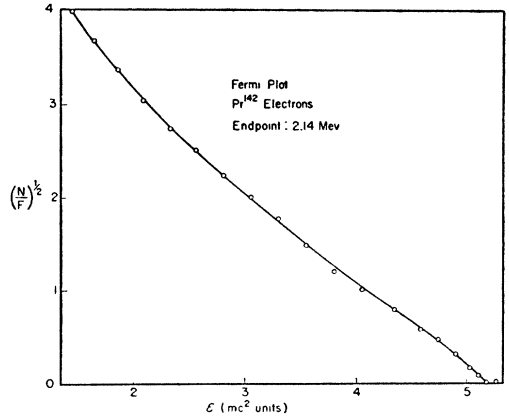

FIG. 4. Fermi plot of Pr^{142} electrons.

atmospheres and a Wulf unifilar electrometer. The sensitivity of this arrangement was determined for each point on the curves by a uranium standard.

Praseodymium oxide bombarded with 10-Mev deuterons yielded a strong rare-earth activity, whose intensity was followed from 200,000 times background to one-tenth background. This decay curve is shown in Fig. 2. From it the half-life was determined to be 19.3±0.1 hours.

The rare-earth fraction from the bombardment of lanthanum oxide with 20-Mev alpha-particles gave an activity, which was followed for 10 half-lives and gave a half-life of 19.2 hours. If any longer period was present, its initial intensity was less than 0.1 percent of the 19-hour period.

Cerium oxide was bombarded with 10-Mev deuterons and 5-Mev protons. From the deuteron bombardment no 19-hour period was found, but from the proton bombardment a 19.3-hour activity was derived.* This decay curve was followed for 12 half-lives. Longer periods, if present, had an initial relative intensity of less than 1 part in 1000.

B. Beta-Ray Spectrum

The beta-ray spectrum of Pr^{142} was measured by a newly constructed magnetic spectrometer of the 180° focusing type, having a radius of curvature of 16 cm. The source holder is similar to that described by Lawson and Tyler.[5] The geometry is determined by three defining slits and an exit slit (3×19 mm), which leads into a Geiger tube filled with hydrogen to a pressure of 8 cm of Hg. The magnetic field is determined by measuring the voltage developed by a small coil rotating at 1800 r.p.m. in the field.[6] The coil is driven by a synchronous motor and is connected through a two-segment commutator to a potentiometer. This method has proved reliable in many calibration tests made on the spectrometer. The magnetizing current is supplied by storage batteries and requires only an occasional adjustment to keep it constant to within 1 part in 1000. The calibration of the field has been checked by measuring the P^{32} electron spectrum and the Cu^{64} electron and positron spectra. These measurements are in excellent agreement with those reported by previous workers.

Figure 3 shows the momentum distribution of the Pr^{142} electrons as found by the magnetic spectrometer. The source was a sample of praseodymium oxide bombarded with deuterons. Impurities other than the rare earths were removed chemically, and a part of the rare-earth precipitate was spread in a thin layer on a strip of thin paper (1 mg/cm²) mounted on the source holder. Counting rates were corrected for counting losses, background counts, the variable H increments, and absorption and scattering by the counter window. Curve (A) shows the entire spectrum plotted from measurements taken thirty-two hours after bombardment. In this case, the maximum counting rate was about 700

* *Note added in proof:* The reaction $Ce^{142}(d, 2n)Pr^{142}$ has recently been obtained with deuteron bombardment of cerium. The 19.3-hour period was established after repeated chemical separations of praseodymium from cerium.

[5] J. L. Lawson and A. W. Tyler, Rev. Sci. Inst. 11, 6 (1940).

[6] R. H. Cole, Rev. Sci. Inst. 9, 215 (1938).

counts per minute. From the two curves, an end point of 2.14±0.02 Mev was found as compared with 2 Mev recently reported.[4]

This value was substantiated by the Fermi plot of curve (*B*) shown in Fig. 4. The points show a definite deviation from a straight line. A consideration of the half-life and the energy on the basis of the Fermi theory shows that the transition ($Pr^{142}\rightarrow Nd^{142}$) is first forbidden.

One gamma-ray was emitted for about every twenty-five beta-rays. This disagrees with the findings of Wu and Segrè,[4] who reported no gamma-rays associated with this period. The lead absorption coefficient for this gamma-radiation was 0.51 cm^{-1}, corresponding to an energy of 1.9 Mev. The decay curve for the gamma-rays gave a half-life of about 19 hours.

III. THE 3.4-MINUTE PERIOD

Praseodymium oxide bombarded with fast neutrons (Li+*d*) gave an activity whose decay curve is shown in Fig. 5. Subtraction of the

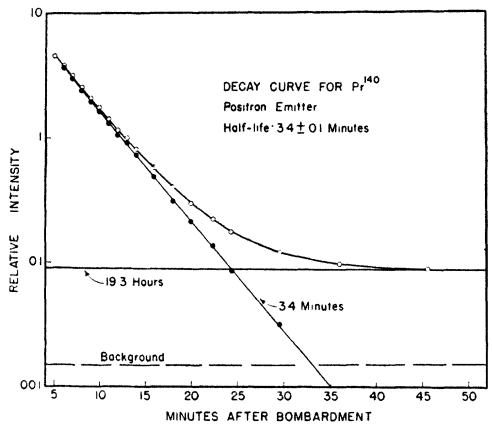

FIG. 5. Decay curve for Pr+fast *n*.

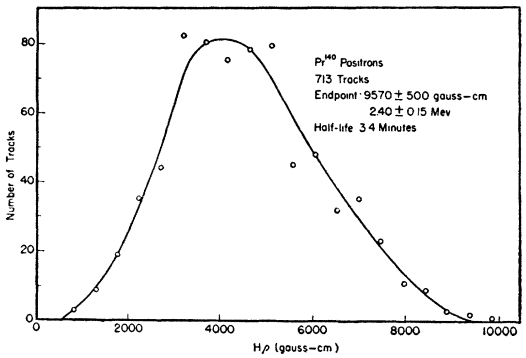

FIG. 6. Momentum distribution of the Pr^{140} positrons.

19.3-hour period, which was due to slow neutrons behind the lithium target, gave a half-life of 3.4±0.1 minutes. No chemical purification was done on this sample. The only positrons obtained from the fast neutrom bombardment were the positrons associated with 3.4-minute period, the 19.3-hour period being an electron emitter. Thus sources were prepared by fast neutron bombardment for a cloud-chamber study of the Pr^{140} positrons.

Figure 6 gives the momentum distribution for the positrons, derived from 713 measured tracks. The end point from this plot was found to be 2.40±0.15 Mev. From the consideration of this value and the half-life, it is probable that ($Pr^{140}\rightarrow Ce^{140}$) is an allowed transition.

It is a pleasure to acknowledge the support received from the University Development Fund and from Mr. Julius F. Stone. Valuable assistance through the W.P.A. cyclotron project No. 65-1-42-89 is also acknowledged. Construction of the spectrometer was supported by a grant-in-aid from the American Association for the Advancement of Science.