New Neutron-Deficient Radioactive Isotopes of the Light Rare-Earth Region*†

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In the light rare-earth region, seven new neutron-deficient radioactive isotopes have been produced by proton bombardment in the 184-in. cyclotron and the linear accelerator; their radiations have been studied by absorption curve and magnetic counter methods. The new isotopes and their half-lives are La^{134}, 6.5±0.25 min; Ce^{133}, 6.30±0.1 hr; Ce^{134}, 72.0±0.5 hr; Pr^{138}, 120±5 min; Pr^{139}, 4.50±0.2 hr; Nd^{138}, 22±2 min; Nd^{139}, 5.50±0.2 hr. Additional data have been obtained for the isotopes, Ce^{135} and Ce^{137}.

I. INTRODUCTION

A MAJOR part of the previous work of synthesis and characterization of neutron-deficient radioactive isotopes in the rare earth region has been done in this laboratory using the 19-Mev deuterons and the 38-Mev helium ions of the 60-in. cyclotron. Thus the conversion of the 184-in. cyclotron to protons and the availability of the proton linear accelerator for bombardment work offer the possibility of producing new activities by (*p*,*xn*) reactions. With the two accelerators approximate maximum proton energies of from 10 to 80 Mev were used to obtain different mixtures of reaction products.

End-on type Geiger-Müller counters were used throughout. The radiations were characterized by absorption curve and magnetic counter data. The results are summarized in Tables I and II.

II. LANTHANUM AND CERIUM ISOTOPES

Lanthanum oxide prepared by Dr. F. H. Spedding served as target material. Spectrographic analysis revealed no other rare earths within the limits of detection, i.e., less than 0.1 percent.

The bombarded material was dissolved in nitric acid and cerous carrier and barium hold-back carrier were added. The material was then subjected to fluoride hydroxide cycles. This consists in precipitating the fluoride from warm nitric acid solution, dissolving the fluoride with 8*N* nitric acid saturated with boric acid, precipitating the hydroxide with ammonium hydroxide, dissolving in nitric acid, and repeating to obtain sufficient purity. The chemistry is specific for rare earths and yttrium.

TABLE I. New isotopes.

Isotope	Radiations	Half-life	Energies in Mev: Particles	Energies in Mev: γ-rays	Produced by
$_{57}La^{134}$	β^+, K	6.5±0.25 min	2.7	no γ	Ce^{134} decay
$_{58}Ce^{133}$	β^+, K, γ	6.30±0.1 hr	1.3	1.8	La(*p*,7*n*)
$_{58}Ce^{134}$	K	72.0±0.5 hr		no γ	La(*p*,6*n*)
$_{59}Pr^{138}$	e^-, β^+, K, γ	120±5 min	0.24(e^-), 1.4(β^+)	0.16, 1.3	Ce(*p*,3*n*)
$_{59}Pr^{139}$	β^+, K, γ	4.50±0.2 hr	1.0	1.0	Ce(*p*,2*n*)
$_{60}Nd^{138}$	β^+, K	22±2 min	2.4		Pr(*p*,4*n*)
$_{60}Nd^{139}$	e^-, β^+, K, γ	5.50±0.2 hr	0.28(e^-), 3.1(β^+)	1.1	Pr(*p*,3*n*)

* This research was done under the auspices of the AEC.
† Portion of dissertation submitted in partial fulfillment of the requirements for the Ph.D. degree at the University of California.

To the purified lanthanum and cerium in nitric acid cooled to 0°C were added first potassium bromate to oxidize the cerium and then iodic acid to precipitate ceric iodate. The coprecipitation of lanthanum is less than two percent by spectrographic analysis, and two reprecipitations of the ceric iodate were sufficient to remove those lanthanum activities which did not grow in rapidly.

Separation of the lanthanum daughter activities was affected by precipitation of the fluoride from the ceric solution. Additional purification was obtained by methods similar to the above.

Proton energies of 50, 60, 70, and 80 Mev were used in the lanthanum (La^{139}, 99.911 percent abundance) bombardments. The 36-hr Ce^{137} observed by Chubbuck[1] was produced in all bombardments, as was Ce^{135}, of estimated 16-hr half-life,[1] which has been shown to be a positron emitter and the parent of the 19.5-hr La^{135}. A 72-hr activity appeared at 60 Mev and in larger amounts at 70 and 80 Mev. At 70 and 80 Mev a 6.3-hr activity was formed. The 72-hr and 6.3-hr periods have been assigned to Ce^{134} and Ce^{133}, respectively.

Ce^{137}

Since this isotope was formed in all lanthanum bombardments, and since its conversion electron is of comparatively high abundance, it was necessary to verify Chubbuck's measurements. The only discrepancy was in the energy of the electron. Magnetic counter measurements and beryllium absorption data both give 0.24 Mev. Decay of the electron through about eight half-lives showed it to be the correct one. A re-examination of Chubbuck's data revealed similar results with an interpretive error on his part.

Ce^{135}

This isotope had been identified as a positron emitter and shown to be the parent of the 19.5-hr La^{135}. A half-life estimate of 16 hr was made by considering the

TABLE II. Revised values.

$_{58}Ce^{135}$	22 hr	0.80 β^+ 0.24 e^-	La(*p*,5*n*)
$_{58}Ce^{137}$			La(*p*,3*n*)

[1] J. B. Chubbuck and I. Perlman, Phys. Rev. **74**, 982 (1948).

areas under the curves from positron sweeps on the magnetic counter. An unusually large cross section for formation of Ce^{137} was offered as explanation for the fact that no 16-hr period could be resolved from decay curves of Ce^{135} and Ce^{137}. However, a more satisfactory explanation is the very low β^+/electron-capture branching ratio for Ce^{135} and the fact that the growth of La^{135} gives an apparent slope of about 36 hr for Ce^{135}.

The cerium fraction from a lanthanum plus 50-Mev proton bombardment, which contained only Ce^{135} and Ce^{137}, was analyzed on the magnetic counter and found to have a 0.81-Mev ($H\rho=4060$ gauss-cm) positron which decayed with a 22-hr half-life.

A beryllium absorption gave a range of 300 mg Be/cm^2 by Feather analysis for the Ce^{135} positron, and 60 mg/cm^2=0.24 Mev for the Ce^{137} conversion electron. Since an unambiguous resolution of decay curves could not be made, no quantitative analysis of Ce^{135} radiations can be offered except that the positron branching is less than one percent.

Lanthanum fractions showed only the 19.5-hr La^{135} and the very long La^{137} which confirms the mass assignment.

Ce^{134} and La^{134}

In all bombardments with protons of 60- to 80-Mev energy, a 72.0-hr cerium activity remained after the other cerium activities had decayed out and their daughter activities had decayed or had been removed by chemical means. Chemical separation of the lanthanum daughter gave a 6.5-min activity.

The La^{133} (4 hr) and La^{135} (19.5 hr) mass assignments have been confirmed mass spectrographically.[2] Since La^{134} is an odd-odd type nucleus, and since La^{136} has a half-life of 10 min,[2] a value of approximately 5 min was anticipated for La^{134}. This evidence plus the approximate threshold energy of 60 Mev for the 72.0-hr cerium constitute the basis for the mass assignment of this pair of isotopes.

A beryllium absorption of Ce^{134} and La^{134} in equilibrium revealed a particle of range 1340 mg Be/cm^2 =2.7 Mev. The magnetic counter proved it to be a positron of maximum energy 2.7 Mev; an end point of $1.06\cdot10^4$ gauss-cm, and positron decay through ten half-lives gave a 72.0-hr half-life. Analysis of the electromagnetic radiation by lead absorption gave only K x-rays and annihilation radiation. The absorption curve data gave the following ratios for the radiations of the two isotopes in equilibrium:

2.7 Mev β^+:K x-rays:0.5 Mev γ=0.44:1.56:0.44.

The L x-rays being of only a few kilovolts energy escape detection by these methods, which constitutes a major error in the radiation analysis.

That the La^{134} daughter emitted the positrons was verified by following the decay of a separated La^{134} sample on the magnetic counter. This was also shown by beryllium absorption (Fig. 1) which was done on the chemically separated daughter. Since the necessarily quick chemistry did not remove all the parent, the beryllium absorption was repeated on the sample as soon as the 6.5-min activity decayed out, and a point-by-point resolution of the absorption curve was made. This method was found to give reproducible results in obtaining absorption data for short-lived activities.

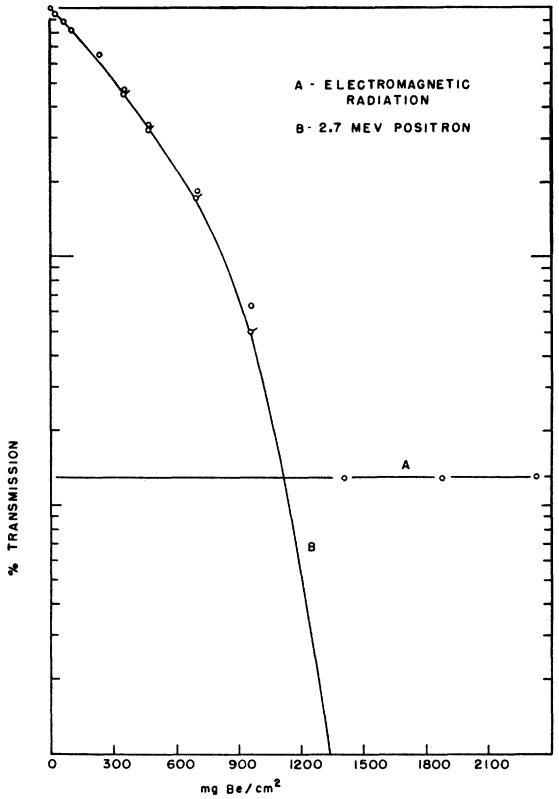

FIG. 1. La^{134} 2.7 Mev positron.

The assumption that, since La^{134} is a positron-emitter, it emits all the positrons, and hence the 0.5-Mev gamma-rays, coupled with the absorption data, allows the following ratios for the La^{134} radiations to be calculated:

2.7 Mev β^+:K x-rays:0.5 Mev γ=0.4:0.6:0.4.

From the above data it can be postulated that the 72.0-hr Ce^{134} decays entirely by orbital electron capture, and that the 6.5-min La^{134} decays 44 percent by positron-emission and 56 percent by electron capture. There are no conversion electrons, and the only gamma is the annihilation radiation.

Ce^{133}

In the bombardments with 70- and 80-Mev protons a cerium activity of shorter half-life which emitted a hard gamma was formed. Since Ce^{134}, Ce^{135}, and Ce^{137} have no gamma-radiation of energy greater than 0.8

[2] Naumann, Reynolds, and Perlman, Phys. Rev. 77, 398 (1950).

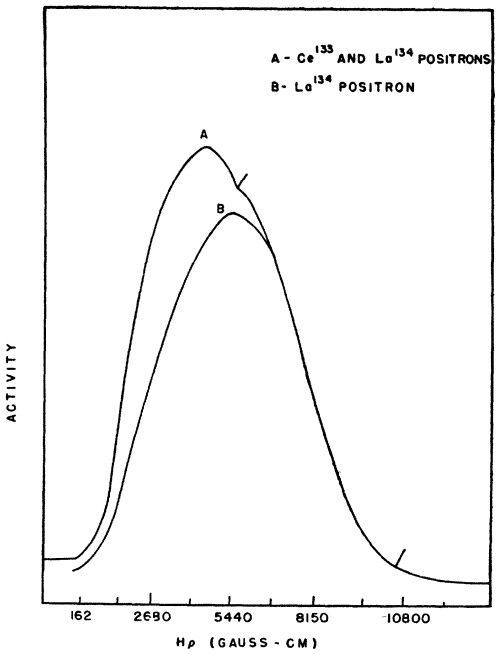

FIG. 2. Ce^{133} and La^{134} positrons.

Mev, an unambiguous half-life determination was possible. The decay of the gamma-radiation through 20 g of lead yielded a 6.3-hr half-life through nine half-lives with a 36-hr tail from the 0.75-Mev gamma of Ce^{137}.

The mass number of the 6.3-hr cerium activity was determined by separating its lanthanum daughter. The 4.0-hr La^{133}, which has been run on the mass spectrograph, was shown to grow in only during the decay of the 6.3-hr activity which must then be Ce^{133}. The approximate threshold of 70 Mev for its formation is also compatible with this assignment.

A satisfactory analysis of the relative abundances of Ce^{133} radiations was not obtained, since the data are complicated by the presence of four cerium activities and the growth of their four daughter activities.

The decay of positrons on the magnetic counter had two components, the 72.0-hr Ce^{134} and an approximately 6-hr one. The positron spectrum indicated two particles as shown in Fig. 2, where curve A was obtained when both activities were present and curve B is the distribution of the 72.0-hr component only. The estimated end point of the 6.3-hr positron is $H\rho = 5680$ gauss-cm $= 1.3$ Mev. The energy was confirmed by beryllium absorption which showed a particle of range 600 mg $Be/cm^2 = 1.3$ Mev in addition to the La^{134} positron and the Ce^{137} 0.24-Mev electron. The data also indicate a conversion electron of about the same energy as the Ce^{137} electron, but this was not unambiguously demonstrated.

The above mentioned hard gamma had a half-thickness in lead of 15 g/cm^2 which corresponds to 1.8 Mev.

Thus the 6.30-hr Ce^{133} decays by orbital electron capture and positron-emission and emits gamma-rays of 1.8-Mev energy.

III. PRAESEODYMIUM ISOTOPES

Cerium metal of 10-mil thickness prepared by Dr. F. H. Spedding was found to be the most satisfactory target material for the study of light praeseodymium isotopes. Traces of calcium and iron were the only impurities detected by spectrographic analysis. An air-tight wrapping of aluminum foil minimized oxidation so that the reaction $O^{18}(p, n)F^{18}$ was not detectable, as it was with the oxide.

The bombarded metal was dissolved in dilute hydrochloric acid, lanthanum carrier for the praeseodymium was added, and then the hydroxides were precipitated with ammonium hydroxide. After dissolving these with concentrated nitric acid and adding potassium bromate, the bulk of the cerium was precipitated as ceric iodate. The lanthanum carrier was then subjected to fluoride hydroxide cycles, and the final step of purification consisted of adding inactive cerium and precipitating to remove the remaining traces of active cerium.

The cerium bombardments were made on the linear accelerator using 10-, 20-, and 32-Mev protons for (p,n), $(p,2n)$, and $(p,3n)$ reactions. Even though cerium has an even atomic number, its isotopic abundances are suitable. The relative abundances are Ce^{142}, 11.07; Ce^{140}, 88.48; Ce^{138}, 0.250; Ce^{136}, 0.193. The contributions of the last two are negligible, and (p,n) on Ce^{142} gives the well-known[3] 19.5-hr Pr^{142}, $(p,2n)$ gives stable Pr^{141}. Thus the reactions of the abundant Ce^{140} can be used to study the neutron deficient praeseodymiums.

At 10 Mev the 19.5-hr Pr^{142} and a 3.5-min period were observed. The 3.5-min half-life has previously been reported[4] for Pr^{140}. At 20 Mev a 4.50-hr, the 19.5-hr, and the 3.5-min activities were formed. A 120-min half-life was seen at 32 Mev only. The 4.50-hr and the 120-min activities have been assigned to Pr^{139} and Pr^{138}, respectively.

Pr^{140}

Pool and Quill[4] reported a 3.5-min positron-emitter from the reaction $Pr^{141}(n,2n)Pr^{140}$. Since a short Pr^{139} was suspected from the decay of Nd^{139}, it was necessary to verify this value. Cerium plus 10-Mev protons gave a 3.5-min half-life through many half-lives as did cerium plus 20-Mev protons.

Pr^{139}

The 4.50-hr praeseodymium activity was formed in bombardments of 20- and 32-Mev protons on cerium but did not appear at 10 Mev. It was thus assigned to Pr^{139} as the product of a $(p,2n)$ reaction on Ce^{140}.

Confirmation of the mass assignment was made by

[3] DeWire, Pool, and Kurbatov, Phys. Rev. **61**, 564 (1942).
[4] M. L. Pool and L. L. Quill, Phys. Rev. **53**, 437 (1938).

showing it to be the parent of the 140-day Ce^{139}. The proton beam of the linear accelerator is much too small to produce sufficient 4.50-hr activity to determine the growth curve of a 140-day activity. A solution containing mainly the 4.50-hr Pr^{139} and a very small amount of the 19.5-hr Pr^{142}, was purified and then allowed to decay for approximately 20 hr. A cerium fraction was then precipitated in which the only cerium activity appearing was Ce^{139}, which must necessarily have grown in from the 4.50-hr activity.

A beryllium absorption showed one particle of range 400 mg Be/cm² which corresponds to 1.0 Mev. The Feather range was found to be the same. This was verified by a magnetic counter sweep which gave a positron of maximum energy 1.0 Mev=4750 gauss-cm.

In addition to the expected K x-rays and annihilation radiation, a 1.0-Mev gamma-ray appeared in the lead absorption.

From absorption data, the relative abundances of these radiations are as follows: 1.0-Mev β^+:K x-rays: 0.5-Mev γ:1.0-Mev γ=0.06:1:0.06:0.04. Since no conversion electrons were observed, it can be assumed that each quantum of K x-radiation represents one disintegration by orbital electron capture. And from the above data it can be postulated that Pr^{139} decays mainly by orbital electron capture with approximately six percent positron branching.

Pr^{138}

In the bombardments with 32-Mev protons a 120-min praeseodymium activity appeared in higher yield than the 4.50-hr Pr^{139}. On the basis of the approximate threshold of 30 Mev, it was allocated to Pr^{138} as the product of a $(p,3n)$ reaction on Ce^{140}.

Decay through 16 g of lead of the abundant hard gamma-ray allowed the 120-min activity to be observed through six half-lives before the amount of Pr^{139} 1.0-Mev gamma became significant.

This isotope emits both a positron and a conversion electron as shown by beryllium absorption, and the magnetic counter. The range of the positron is 625 mg Be/cm², which was verified by Feather analysis, and the visual end point of the magnetic counter sweep is 6140 gauss-cm, both of which correspond to a maximum energy of 1.4 Mev. The values 50 mg Be/cm² and 1740 gauss-cm show the energy of the conversion electron to be 0.22 Mev.

Gamma-rays of half-thicknesses 0.275, 4.5, and 12.0 g Pb/cm², corresponding to 0.16, 0.5, and 1.3 Mev, and K x-radiation appeared in the lead absorption. From absorption data the relative abundances of the radiations are as follows: 0.22-Mev e^-:1.4-Mev β^+: K x-rays:0.5-Mev γ:1.3-Mev γ=0.04:0.14:1:0.22:0.36:0.75.

If it is assumed that four percent of the K x-radiation arises from the process of conversion, an approximate branching ratio of positron-emission to electron capture of 0.13:1 is obtained for the decay of Pr^{138}. The high abundance of the 0.5-Mev gamma-radiation indicates a gamma of approximately 0.5 Mev in addition to the annihilation radiation.

IV. NEODYMIUM ISOTOPES

The target material for these experiments was praeseodymium oxide from Johnson Matthey Company, sample No. 547 which had been further purified on an ion exchange column by Mr. R. C. Lilly of this laboratory. No impurities were detected by spectrographic analysis.

The bombarded material was dissolved in nitric acid and a pure rare-earth fraction was obtained by fluoride hydroxide cycles.

The neodymium activities were separated from the praeseodymium target material of an ion-exchange column.

Protons of energies 40 and 50 Mev gave a 22-min activity, a 5.50-hr one, and the 3.3-day Nd^{140} reported by Hicks and Wilkinson.[5] The 145-min Nd^{141} was[5] not observed at these energies. The 5.50-hr Nd was shown to be the grandparent of the 140-day Ce^{139} and thus is Nd^{139}. The 22-min period is tentatively assigned to Nd^{138}, since its yield relative to Nd^{139} is greater at 50 Mev than at 40 Mev.

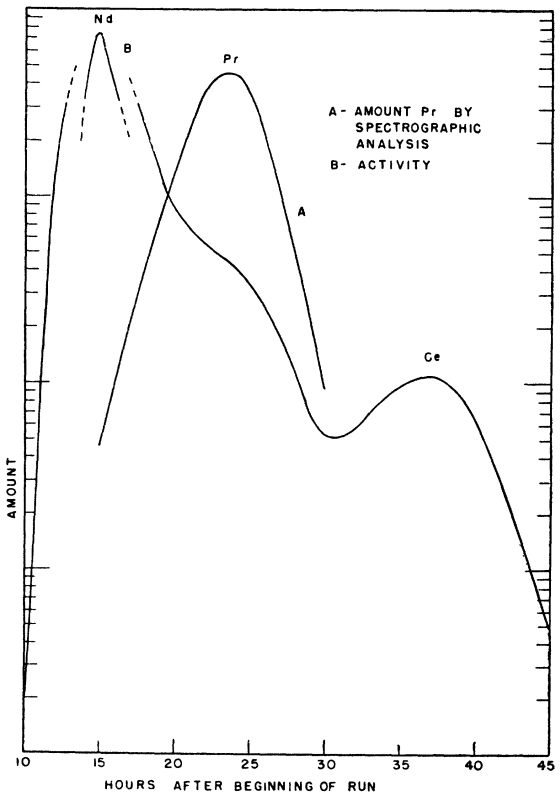

FIG 3. Column separation of Nd^{139}.

[5] H. G. Hicks and G. Wilkinson, Phys. Rev. **75**, 1687 (1949).

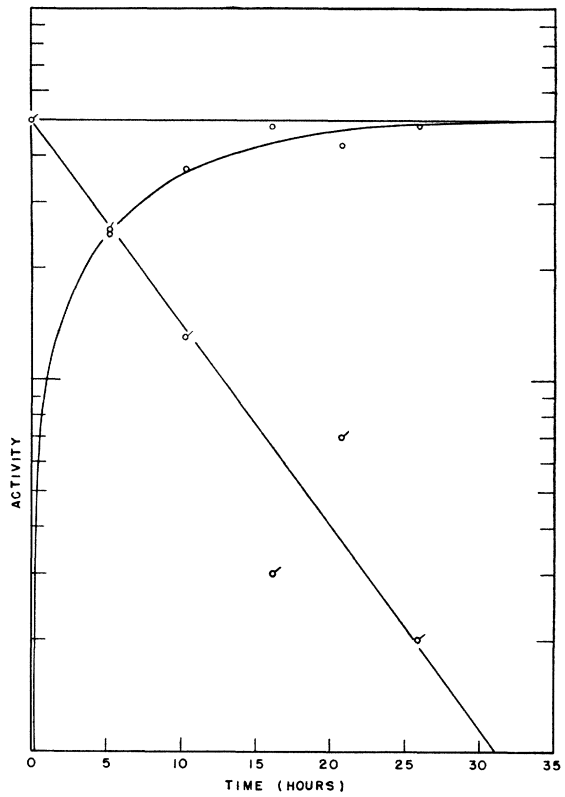

FIG. 4. Growth of 140-day Ce^{139} from 5.50-hr Nd^{139}.

Nd^{139}

The 5.50-hr activity formed by bombarding praeseodymium with 40- and 50-Mev protons was found to emit hard gamma-radiation of greater relative abundance than the 3.3-day Nd^{140} which was also formed. This made possible a good half-life determination by following decay through 16 g of lead.

The chemical identification was made by means of an ion exchange column. The target material, after being purified by fluoride hydroxide cycles and dissolved in dilute hydrochloric acid, was warmed with a small amount of resin for about five minutes, after which time it was placed on the resin in the column and eluted with citrate.

Since the elution of light rare earths is quite slow, a short column was necessary in the identification of a 5.50-hr activity. A length of 4 cm and a cross section of 0.317 cm^2 for the resin, which was the ammonium form of Dowex-50 spheres, an aromatic hydrocarbon polymer containing nuclear sulfonic acid groups as the only active exchange groups,[6] gave satisfactory separation. The flow rate was 0.06 ml min^{-1} cm^{-2}, and the eluting agent was 0.5M citric acid to which sufficient ammonium hydroxide was added to obtain a pH of 3.15.

[6] W. C. Bauman and J. Eichhorn, J. Am. Chem. Soc. **69**, 2830 (1947).

The elution curve is shown in Fig. 3. Curve A shows the position of the target material and was determined by spectrographic analysis. Curve B represents the elution of the activity. It is not an accurate representation of the shape of the curve, since it was not corrected for decay. However, it is an accurate representation of the position of the peak, since decay of samples taken at the peak and on both sides of it when extrapolated to an arbitrary time showed a constant ratio of 5.50-hr activity to 3.3-day Nd^{140}. This proves that the 5.50-hr activity is neodymium.

The broad shoulder of curve B under curve A is in part the 4.50-hr Pr^{139} daughter, but the elution time is too long relative to the time for growth and decay to detect any distinct separation with the similarity of half-lives. After many hours the 140-day Ce^{139} granddaughter appeared.

The mass number was confirmed by separating Ce^{139} from an approximately equilibrium mixture of Nd^{139} and Pr^{139}. The 140-day Ce^{139} was found to grow in with a 5.50-hr half-life (Fig. 4).

In the analysis of the Nd^{139} radiations an uncertainty was introduced by the presence of a small but unknown amount of Pr^{139} daughter. In short bombardments a (p,p) reaction to give the 3.5-min Pr^{140} was detected at 50 Mev but not at 40 Mev. From this it was assumed that the amount of (p,pn) reaction to give Pr^{139} was

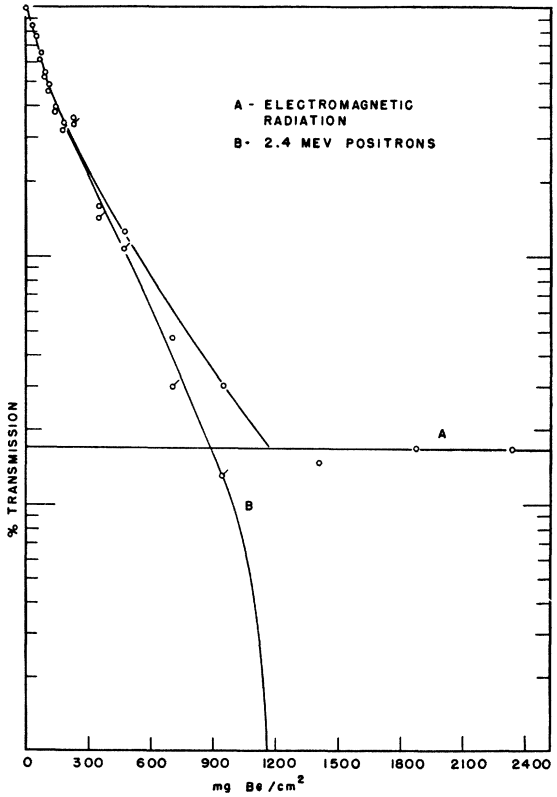

FIG. 5. Be absorption of 22-min Nd^{138}.

negligible at 40 Mev. The absorption data were obtained as soon after bombardment as possible when a minimum of Pr^{139} was present.

Beryllium absorption showed two particles of ranges 70 and 1560 mg Be/cm² corresponding to 0.28 and 3.1 Mev, respectively. These were shown to be a conversion electron and a positron on the magnetic counter, and the energies were verified, for the conversion electron, $H\rho = 2010$ gauss-cm $= 0.28$ Mev, and for the positron, $H\rho = 1.19 \cdot 10^4 = 3.1$ Mev. The sweeps were taken a number of hours after bombardment and the curious shape of curve B results from the 1.0-Mev Pr^{139} positron which had grown in, the presence of which in no way affects the determination of the Nd^{139} positron end point.

In addition to the K x-rays and the annihilation radiation, a gamma-ray of half-thickness 12.5 g Pb/cm² = 1.3 Mev was detected by lead absorption.

The relative abundances of these radiations, subject to the uncertainty introduced by daughter growth, are as follows: 0.28-Mev e^-: 3.1-Mev β^+: K x-rays: 0.5-Mev γ: 1.3-Mev $\gamma = 0.03 : 0.11 : 1 : 0.11 : 0.10$.

From these ratios it can be postulated that Ne^{139} decays mainly by electron capture, and, assuming that each K x-ray quantum represents one disintegration by electron capture, the positron branching is approximately 10 percent.

Nd^{138}

A 22-min activity was formed in the bombardments of praseodymium with 40- and 50-Mev protons, and appeared in greater yield relative to Nd^{139} at 50 Mev. It was shown to be a rare earth by fluoride hydroxide cycles, and, since Nd^{139}, Pr^{139}, and Pr^{138} have been identified, the 22-min activity is tentatively assigned to Nd^{138}.

A beryllium absorption was taken of the 22-min activity, and, after it was gone, the absorption was repeated on the Nd^{139}. A point-by-point resolution shows a particle of approximate range 1160 mg Be/cm² corresponding to a maximum energy of 2.4 Mev (Fig. 5). It undoubtedly is a positron, and the shape of the curve indicates that there may also be a conversion electron.

I wish to thank Dr. B. B. Cunningham under whose direction the work was done, Mr. J. T. Vale and the crew of the 184-in. cyclotron, Mr. R. D. Watt and the crew of the linear accelerator, Mr. J. Conway and Mr. M. Moore of the spectrographic laboratory, and Dr. LeRoy Eyring who participated in the study of Nd^{139}.

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Energy Degeneration of Cosmic-Ray Primaries*

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Under the assumptions that a meson-producing collision between two nucleons with relativistic energies is completely inelastic and that the collision cross-section is independent of energy, one can calculate the energy degeneration of the primary cosmic rays (assumed to be nucleons) and the energy spectrum of high energy nucleons as a function of depth in the atmosphere for any primary spectrum. While this model is highly restricted, it is of considerable interest for comparison with experimental results, since it leads to the maximum possible rate of energy degeneration for nucleons. Binding of nucleons into nuclei is neglected (except for the "packing effect" on the mean-free-path for collision) and the results are further limited to energies greater than 1 Bev where energy loss due to ionization is negligible and the velocity of the nucleons may be taken to be the velocity of light. Analytic solutions are obtained for the energy spectrum at any depth for monoenergetic and power-law primary spectra. The effect of the geomagnetic cut-off on a primary power-law spectrum is also investigated.

I. INTRODUCTION

RECENT cosmic-ray investigations,[1] particularly those at high altitudes, have accumulated a body of experimental evidence favoring a coherent interpretation of cosmic-ray phenomena in terms of the identification of the majority of cosmic-ray primaries as *nucleons* (either free (protons) or bound in nuclei[2]) and for meson-producing collisions (or, more generally, nuclear interactions) as the principal agency for their rapid absorption in the atmosphere. The variety of

* Part of the work herein contained formed a portion of a thesis submitted by one of the authors (F.J.M.) in partial fulfillment of the requirements for the degree of Bachelor of Science in Physics. A preliminary report on this work was made at the semi-centennial meeting of the American Physical Society, Cambridge, Massachusetts, June 16–18, 1949.

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[1] See, for example, W. Heisenberg, Ed., *Cosmic Radiation* (Dover Publications, 1946); B. Rossi, Rev. Mod. Phys. **20**, 537 (1948); Proceedings of the Symposium on Cosmic Rays at the California Institute of Technology, June 21–25, 1948, Rev. Mod. Phys. **21** (1949).

[2] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948); Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. **74**, 1818 (1948); H. L. Bradt and B. Peters, Phys. Rev. **74**, 1828 (1948).