21 barns, and for an assumed square-well n-p interaction they imply a force range of 1.54×10^{-13} cm, experimental error allowing this value to lie between 1.12 and 1.99×10^{-13} cm.

6. ADDITIONAL ACKNOWLEDGMENTS

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Search for Positron-Electron Branching in Certain Beta Emitting Isotopes

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The β-rays emitted by the isotopes Ga^{70}, As^{76}, Br^{80}, Br^{82}, Rb^{86}, Rh^{104}, Ag^{108}, In^{116}, Sb^{122}, Sb^{124}, I^{128}, Re^{186}, and Au^{198} have been examined for positrons by the "trochoidal" method of Thibaud. Br^{80} is the only one of the above isotopes which was found to emit positrons as well as electrons. In studying Rb, a new activity of about 40-day half-life was found.

1. INTRODUCTION

WHEN a radioactive isotope of charge Z is isobaric with stable isotopes of charge $Z-1$ and $Z+1$ there exists the possibility of decay by positron emission or orbital electron capture as well as by electron emission. There are many isotopes in this situation, yet only a few of them are known to emit both positrons and electrons. The present experiments were undertaken with the idea that a sensitive detection method might show this branching in cases where it had hitherto been undetected. The trochoid provides an efficient means of making a complete separation of positrons and electrons, hence it was selected for the experiments.

2. EXPERIMENTAL APPARATUS

The trochoid was first used by Thibaud[1] to verify the existence of positrons and to study some of their properties. The instrument as used in the present experiments is simply a brass vacuum chamber shaped like a 270-degree section of a doughnut. A source is placed at one end of the chamber, and a Geiger-Müller counter is mounted at the other. The chamber fits between the poles of a circular-pole electromagnet in such a way that electrons from the source describe trochoidal paths around to the detector. When the magnet current is reversed only positrons can reach the detector. A diagram of the apparatus with a possible electron trajectory is shown in Fig. 1.

To make the source readily changeable a vacuum tight "well" with a 0.001-in. copper window was mounted in the source position. Absorption of the β-rays was studied by putting aluminum absorbers in the well between the source and the window. In experiments where it was desirable to have a minimum of absorbing material between source and detector the well was not used, and the source was mounted directly inside the vacuum chamber.

The counter had a 0.001 inch aluminum window which was waxed onto a cylindrical brass shell. The brass shell had three slots on one side through which the β-particles entered. Plateaus of about 100 volts were obtained when the counter was filled with 3 cm of argon and 2 cm of alcohol.

The apparatus was tested by measuring the relative number of positrons and electrons emitted by Cu^{64}. It was found, as is well known,[2] that the observed ratio of electrons to positrons depends on the source thickness and on the counter-window thickness. With a source 0.0002 in. thick and a 0.001-in. aluminum counter

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[1] J. Thibaud, Phys. Rev. **45**, 781 (1934).

[2] K. Sinma and F. Yamasaki, Scientific Papers of the Institute of Physical and Chemical Research, Tokyo, **35**, 16 (1938).

TABLE I. Data on nuclei examined for positron emission.

Isotope	Half life	Upper limit for ratio of positrons to electrons	Window thickness source and counter mg/cm^2 aluminum equivalent
Ga^{70}	20 min.	0.005	30
As^{76}	27 hrs.	0.0003	14
Br^{80}	18 min.	0.03*	30
Br^{82}	34 hrs.	0.004	30
Rb^{86}	19.5 days	0.003	13
Rh^{104}	4.2 min.	0.001	30
Ag^{108}	2.3 min.	0.005	7
In^{116}	54 min.	0.001	24
Sb^{122}	2.8 days	0.001	30
Sb^{124}	60 days	0.005	13
I^{128}	26 min.	0.002	30
Re^{186}	90 hrs.	0.001	7
Au^{198}	2.7 days	0.001	7

* Observed ratio.

window the ratio was 1.6 which is in agreement with the results of Sinma and Yamasaki.[2]

Also it was found that the counting rate observed with a given sample increases slightly as the magnetic field is increased. For example, measurements on the electrons from Rb^{86} ($E_0 = 1.6$ Mev) showed that the counting rate increased 6 percent when the magnetic field was increased from 9000 to 9500 gauss at the center of the magnet. This effect probably arises from the better focussing of the β-particles by the higher fields, and thus with a constant magnetic field the counting efficiency of the apparatus depends slightly on the energy of the β-rays being examined. In the present experiments the results are rough, and any errors introduced by this effect are negligible.

Because many of the isotopes emit γ-rays, which cannot be completely shielded from the counter, finding a method of determining the background counting rate is somewhat of a problem. In these measurements the background was found in one of two ways. When the sample was placed inside the vacuum chamber, the background count was made with the magnetic field equal to zero. In this case a correction of about 20 percent was required because the counter was less efficient with the field on. When the sample was placed in the source well, the background was taken by leaving the magnetic field unchanged and putting an aluminum absorber of 700 to 1000 mg/cm^2 in front of the source.

Energy measurements of the β-rays were made in the trochoid by the method of absorption in aluminum. In order to be certain that the usual relation between range and upper energy limit is valid for absorption measurements made in the strong magnetic field of the trochoid, absorption curves were taken on the electrons from P^{32} ($E_0 = 1.72$ Mev) and Br^{82} ($E_0 = 0.47$ Mev). The Feather relation with the constants given by Bleuler and Zünti[3]

$$R\ (\mathrm{g/cm^2}) = 0.571 E_0\ (\mathrm{Mev}) - 0.161 \qquad (1)$$

yielded the known upper energy limits within experimental error.

All of the isotopes studied were produced by (n,γ) reactions, using the neutrons produced by the 60-inch cyclotron in Berkeley. The neutrons were slowed by surrounding the sample with paraffin, but the amount of paraffin was not sufficient to eliminate the $(n,2n)$ reaction.

In the study of bromine, sources of high specific activity were obtained by the method of Szilard and Chalmers.[4]

3. EXPERIMENTAL RESULTS

Table I lists the isotopes which were studied. Each of these is known to be an electron emitter. The only one which was found also to emit positrons is Br^{80}. When the magnetic field was

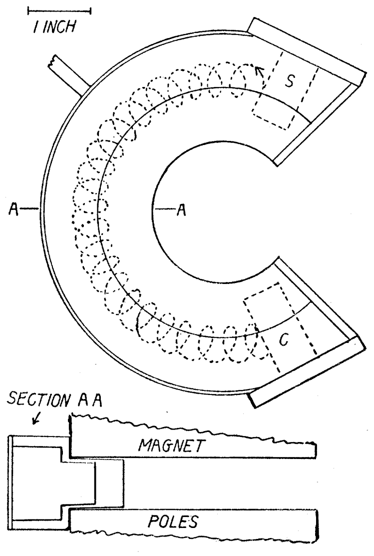

FIG. 1. Drawing of the trochoid. The positions of the source and counter are shown in dashed lines at S and C. An electron trajectory is shown as a dashed curve from the source to counter.

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[3] E. Bleuler and W. Zünti, Helvetica Physica Acta **19**, 375 (1946).

[4] L. Szilard and T. A. Chalmers, Nature **134**, 462 (1934).

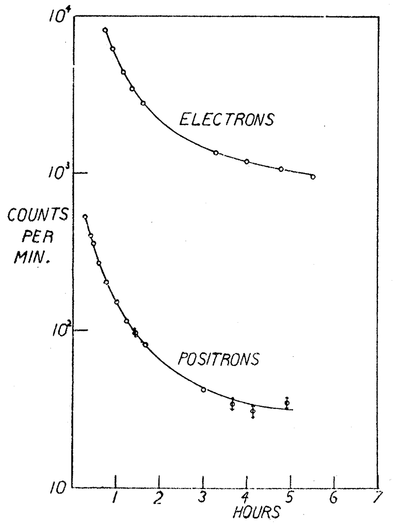

FIG. 2. Decay curves of the electrons and positrons emitted by Br^{80}. The ratio of electrons to positrons is equal to 35.

set for positrons, each of the other isotopes gave a counting rate which was not significantly different from the background counting rate. An estimate of the number of positrons which could have been detected is also given in Table I. This ratio has been calculated by assuming that positrons would have been detected if they had been present in greater numbers than four times the standard error in the background counting rate. Thus

$$\text{upper limit for the ratio of positrons to electrons} = (4/N_e)(N_b/T)^{\frac{1}{2}}, \quad (2)$$

where N_b = background counting rate; N_e = electron counting rate; T = time of counting the background. T is also equal to the time of counting positrons.

That the positrons emitted by the bromine sample belong to the isotope Br^{80} is shown in an interesting way by following the decay curves of the electrons and positrons from the same sample. The observed decay curves are shown in Fig. 2. The explanation of the curves follows from the well-known fact[5] that Br^{80} has an upper isomeric state of half-life 4.4 hours which always decays to the lower state. The lower state decays with half-life 18 minutes to Kr^{80} or Se^{80}. Bombardment of Br with slow neutrons produces both states, hence the decay curve shows first an 18-minute period which goes over into the 4.4-hour period as soon as all the original lower state nuclei are gone. The positron decay curve has the same form as the electron decay curve, and the ratio of electrons to positrons is independent of time and has the value 35.

The absorption of Br^{80} positrons in aluminum is plotted in Fig. 3. The background, caused chiefly by the γ-rays from Br^{82}, did not permit the absorption measurement to be made down to 10^{-3} of the initial intensity. Comparison, by the method of Feather,[6] of this absorption curve with the curve taken using P^{32} yields $E_0 = 0.73$ Mev. (The error in this result could be as much as 0.1 Mev.) According to Eq. (1) this corresponds to a range of 0.26 g/cm^2 which is about what one would estimate from the shape of the curve.

The elements arsenic and rubidium showed slight positron activities after bombardment with neutrons from the cyclotron. However, careful study showed that these positrons followed decay curves different from those of the isotope under study.

In the case of arsenic the positron activity amounted to only 0.05 percent of the electron activity and the decay curve indicated that these positrons could be attributed to As^{74}, formed by an $(n,2n)$ reaction. This result is in

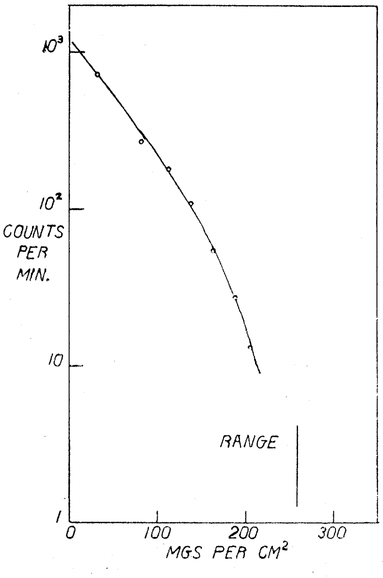

FIG. 3. Absorption of the Br^{80} positrons in aluminum. The data were corrected for decay of the sample and the background was subtracted before the curve was plotted. The range is estimated as 0.26 g/cm^2.

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[5] E. Segrè, R. S. Halford, and G. T. Seaborg, Phys. Rev. **55**, 321 (1939).

[6] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

disagreement with a report by Harteck, Knauer, and Schaeffer[7] that approximately 2 percent of the As^{76} atoms decay by positron emission.

The neutron bombarded rubidium showed a positron activity of about one percent of the electron activity, with the positron activity having a somewhat longer half-life. This new positron activity was measured again in a strong sample of rubidium which was produced by bombarding strontium with 18-Mev deuterons from the 60-inch Berkeley cyclotron. The rubidium was chemically separated from the other reaction products, and the half-life of the positron activity was measured roughly as 40 days. These two methods of production suggest that the activity is due to Rb^{84}, which could decay to Kr^{84} by positron emission, from the reactions

$$Rb^{85}(n,2n)\rightarrow Rb^{84}, \quad Sr^{86}(d,\alpha)\rightarrow Rb^{84}.$$

Study of this activity is being continued.

4. DISCUSSION

It is interesting that all of the isotopes which were studied prefer to decay by electron emission. This result can be explained by the fact that all the radioactivities were produced by (n, γ) reactions on stable isotopes. In the present study only those radioactive isotopes which have stable isobars with Z smaller or larger by one were investigated. This type of radioactivity only occurs in elements of odd Z; these have only one or two stable isotopes. Thus capture of a neutron usually yields a radioactive isotope which is on the excess neutron side of the stability curve.

As a check on this hypothesis, a survey of the isotope chart was made for all known radioactive isotopes which have stable isobars on each side. Forty such isotopes whose assignment was considered reliable were found. Twenty-one occur in elements with one stable isotope and nineteen in elements with two stable isotopes.

When there is only one stable isotope, those cases which have more neutrons than the stable one include ten electron emitting isotopes and three isotopes which show branching decay. Those cases which have fewer neutrons than the stable one include four which emit positrons or capture orbital electrons, one which emits electrons, and three with branching decay.

The elements with two stable isotopes show even more rigid behavior. When the radioactive isotope has more neutrons than the heavier stable isotope, it is always an electron emitter (four cases). When the radioactive isotope has fewer neutrons than the lighter stable isotope, it is always a positron emitter (four cases). When the radioactive isotope lies between the two stable ones, it is sometimes an electron emitter (seven cases) and sometimes shows branching decay (four cases).

These statistics clearly indicate that the radioactive isotope usually decays toward the isobar which is nearer the stability curve.

It is possible also to estimate the energy difference of two of these isobars as follows. Measurements with the trochoid indicate that except for Br^{80}, the isotopes measured have a ratio of electrons to positrons which is approximately 500 or greater. From the Fermi theory of beta decay it is possible to calculate what difference in energy will produce a ratio of approximately 500 electrons to one positron. If the positron and electron transitions are equally allowed, and if the maximum total energy, W_0, of the electron spectrum is twice that of the positron spectrum, then the ratio of electrons to positrons will be approximately 500. (W_0 is equal to the maximum kinetic energy of the β-particle plus its rest energy.) (In the case of Br^{80} the electron decay must be one degree more forbidden than the positron decay because in this case the ratio of the total energies is just two.)

Thus the fact that no positrons are observed usually means that the total energy of the transition from the isotope of charge Z to the isobar $Z+1$ is at least twice as great as the total energy of the transition to the isobar $Z-1$.

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[7] P. Harteck, F. Knauer, and W. Schaeffer, Zeits. f. Physik **109**, 153 (1938); *ibid.* **113**, 287 (1939).