Experimental Evidence for the Existence of a Neutrino

JAMES S. ALLEN
Kansas State College, Manhattan, Kansas
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Radioactive Be^7 was deposited on a platinum foil by means of a new evaporation technique. An electron multiplier tube was employed to count the recoil nuclei produced in the reaction, $Be^7+e_K\rightarrow Li^7+\eta+Q$. The maximum energy of the recoils was about 40 to 45 electron volts compared with the value of 58 electron volts to be expected for a neutrino of zero rest mass. An attempt was made to detect coincidences caused by the emission in opposite directions of a gamma-ray and a recoil nucleus. The observed coincidences were less than two percent of those expected for gamma-ray recoils. Apparently the recoils were caused by the emission of a neutrino and not by the emission of a gamma-ray.

INTRODUCTION

THE assumption of the existence of a neutrino is necessary for the conservation of spin and energy in the continuous beta-ray spectrum. Since the neutrino has no charge, an extremely small magnetic moment (if it has one at all), and a very small rest mass, probably the only experimental method for its detection is the observation of the recoil of the nucleus produced in a radioactive decay requiring the emission of a neutrino. Since the beta-ray decay is essentially a three-body process, it is necessary to measure the momenta of both the electron and the nucleus and also the angle between these two momenta in order to find the momentum of the neutrino and finally its mass.

Crane and Halpern[1] attempted to discover the neutrino by measuring the recoil of the electrons and nuclei produced in the disintegration of radiochlorine. Cl^{38} emits negative electrons and has a half-life of approximately 37 minutes. The radioactive substance was introduced into a cloud chamber as a gas, ethylene dichloride. The momentum of an electron emitted during the decay of a radioactive atom could be measured from the curvature of the cloud track in a magnetic field. However, the energy of a recoil nucleus was so small that only a cluster of droplets at the origin of a beta-ray track was produced in the chamber. Since little is known about the energy range relation of very slow atoms in gases, the momenta of the recoil nuclei could not be measured with any accuracy. Although this method was refined somewhat in another experiment, no very definite evidence regarding the neutrino was discovered. The authors concluded that the observed recoil momenta were greater than expected, when no neutrino was assumed.

Leipunski[2] has given a very brief report of an experiment in which radiocarbon was used. C^{11} has a half-life of about 18 minutes and is a positron emitter. The C^{11} was adsorbed as CO_2 gas on a plate cooled by liquid air. The recoil nuclei were accelerated from the plate to a cup-shaped disk by a potential of 5000 volts. Secondary electrons ejected from this disk were recorded by a point counter placed near it. The energy of the recoils was measured by a retarding field between the source plate and a grid. The author concluded that his retarding potential data showed relatively more recoils at the high energy end of the curve than predicted without the assumption of a neutrino.

The decay process involving the capture of an orbital K electron offers another possibility for the detection of the neutrino. The decay of Be^7 is the best example of this process. Kan Chang Wang[3] recently has suggested the use of this substance in a neutrino experiment. The most extensive work on the properties of Be^7 has been done by Rumbaugh, Roberts, and Hafstad.[4] According to these authors, the nuclear reac-

[1] H. R. Crane and J. Halpern, Phys. Rev. **53**, 789 (1938) and Phys. Rev. **56**, 232 (1939).

[2] A. I. Leipunski, Proc. Camb. Phil. Soc. **32**, 301 (1936).

[3] Kan Chang Wang, Phys. Rev. **61**, 97 (1942).

[4] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).

tions are

$$\left.\begin{array}{l} Li^6+D^2\rightarrow Be^7+n+(3.3\text{ Mev}) \\ Be^7+e_K\rightarrow Li^7+\eta+(1\text{ Mev}) \\ Be^7+e_K\rightarrow (Li^7)^*+\eta+(0.55\text{ Mev}) \\ (Li^7)^*\rightarrow Li^7+h\nu+(0.45\text{ Mev}) \end{array}\right. \begin{array}{l} \\ \text{half-life,} \\ \text{43 days} \\ \\ \end{array}$$

where e_K, n, and η represent, respectively, a K electron, a neutron, and a neutrino. The decay process is unique in that neither positive electrons nor negative electrons are emitted. The decay is indicated solely by the 0.45-Mev gamma-rays which were shown to be emitted in about one-tenth of the total number of disintegrations. According to the more recent experiments of Haxby[5] and collaborators on the threshold for the reaction $Li^7(p, n)Be^7$, the atomic mass difference Be^7-Li^7 is 0.87 Mev. Therefore, the energy released during the decay of Be^7 is 0.87 Mev instead of 1.0 Mev.

Since the Be^7 decay is not complicated by the emission of electrons, the recoil of the nucleus, if observed, should be entirely due to the ejection of the neutrino. It is necessary only to measure the momenta of the recoil Li^7 nuclei since it is difficult to see how the energy and momentum can be carried away without the neutrino. With the assumption of zero rest mass for the neutrino, the recoil Li^7 nuclei should have a maximum energy of 58 electron volts. The Li^7 recoil nuclei resulting from the emission of the 0.45-Mev gamma should have a maximum energy of 15.6 electron volts.

Since the recoils have so little energy, it is evident that the experiment must be carried out in a vacuum. The electron multiplier tube offered an excellent possibility of detecting the slow recoil atoms or ions.

PREPARATION OF THE RADIOACTIVE SOURCE

Since it was desirable that the recoil Li^7 nuclei be ejected from the source as positive ions, it was evident that the Be^7 should be placed on a platinum surface. According to the well-known theory of surface ionization, the ejected Li^7 atoms should be ionized upon leaving the metal surface since the electron work function of platinum is much greater than the first ionization potential of lithium.

[5] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).

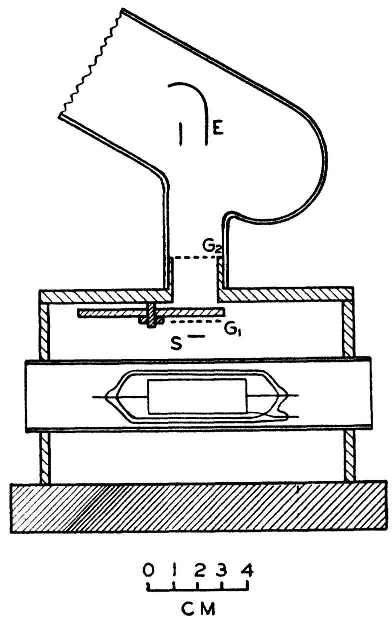

FIG. 1. Experimental arrangement of G-M and electron multiplier tubes.

The first experiments were carried out with a sample of lithium metal that had been bombarded with 8-Mev deuterons in the University of Chicago cyclotron. The lithium was converted to LiCl. After the salt had been dried, a sample was placed in a small steel furnace and evaporated in a vacuum. The evaporated LiCl was collected in a beaker inverted over the furnace. It was found that the total activity remained in the furnace although practically all the sample had been evaporated.

A LiF sample was obtained which had been bombarded with 250-microampere hours of 8-Mev deuterons. A sample of this salt was fused to a strip of one mil thick platinum foil. The activity was measured with a G-M tube and then the material was evaporated at a temperature of about 800°C in a vacuum. The activity of the strip after the complete evaporation of all the LiF was 80 to 90 percent of the original activity. This suggested that the BeF_2 was reduced to Be in the presence of the alkali metal and remained as metallic beryllium. This process was continued until the whole sample had been placed on the platinum strip covering an area of about one square centimeter.

The strip was heated to a temperature of about 1450°C for several hours in a vacuum. Although

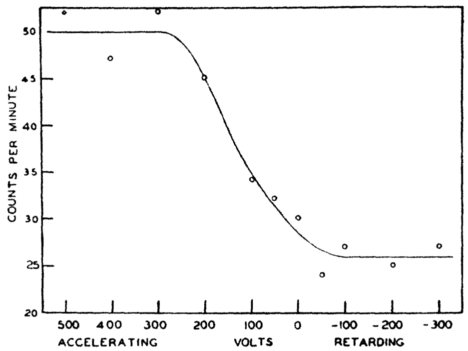

FIG. 2. Retarding potential curve for recoil ions produced by the disintegration of Be^7.

considerable platinum was evaporated, very little activity was lost. This indicated that the radioactive atoms had diffused into the metal. If the platinum could be evaporated rapidly enough, some of the radioactive atoms should be exposed on the surface. However, it remained to be seen whether or not a sufficient surface concentration of radioactive atoms could be obtained in this manner. During the rapid evaporation the temperature of the strip was raised too high and the foil melted through at the center. The pieces of this strip contained about 50 percent of the original activity and were used in the neutrino experiment. The source was spot welded to a tantalum strip so that it could be heated by a current passed through the tantalum.

The radioactivity was identified as that of Be^7 by measuring the absorption coefficient of the radiation in lead. This corresponded to a gamma-ray of about 0.45 Mev. The half-life was found to be in agreement with the value of 43 days reported by Rumbaugh, Roberts, and Hafstad.[4]

EXPERIMENTAL PROCEDURE

A diagram of the apparatus used is shown in Fig. 1. The electron multiplier was of the type described by Allen[6] and had 11 beryllium-covered electrodes. The first electrode E was at a potential of about 3.6 kv negative with respect to ground. The platinum source strip S was supported by two copper rods passing through the base of the apparatus and could be heated by a current sent through these electrodes. A small G-M tube was placed inside a brass tube having a wall thickness of 1/32 inch. Since this tube passed through the outer walls of the vacuum chamber, it was not necessary to bring the G-M tube leads through the vacuum. The multiplier tube could be shut off from the rest of the apparatus during the heating of the source by a gate of $\frac{1}{8}$-inch steel rotated by means of a magnet. The grids G_1 and G_2 were of copper screen; G_2 was at ground potential while G_1 was supported by insulators. A three-stage oil diffusion pump was used to evacuate the apparatus.

Since the pulses from the multiplier tube have an almost random distribution in size, it was necessary to use a pulse equalizing circuit before coincidences between pulses from both the G-M tube and the multiplier tube could be obtained. The multiplier tube pulses were amplified in a two-stage resistance capacity coupled circuit with considerable degeneration between the second and first tube. The pulse equalizer consisted of a multivibrator circuit with time constants sufficiently small so that the width of the pulses was not increased. A high negative grid bias at the second tube kept the circuit from oscillating after a pulse had tripped it. This circuit was found to be extremely convenient since by suitable adjustment of the grid bias voltage, the amplifier noise could be eliminated and all the pulses higher than this noise level brought to a uniform height.

The pulses from the G-M tube were amplified by means of a Neher-Harper circuit. For co-

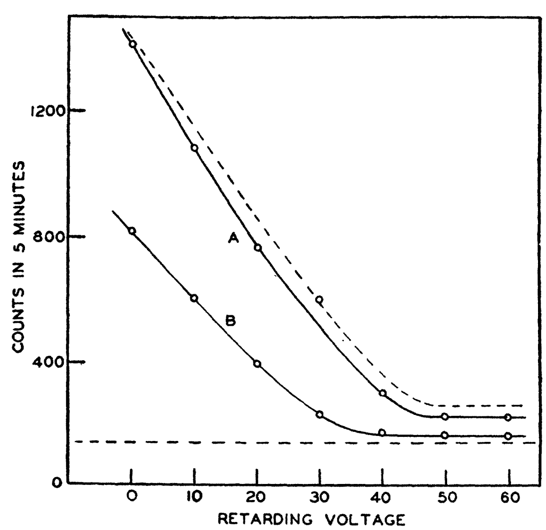

FIG. 3. Retarding potential curves for recoil ions. The horizontal dotted line represents the background counting rate.

[6] James S. Allen, Rev. Sci. Inst. 12, 484 (1941).

incident counting the pulses from both circuits were mixed in a self-stopping thyratron stage. A scale-of-eight circuit was used to record the pulses.

RESULTS

Before the radioactive source was placed in the apparatus, the multiplier tube had a background counting rate of about four per minute. During the experiment some Li or LiF was evaporated onto the electrodes and the background increased to 40 per minute.

When the Be^7 source was placed in the apparatus, no recoil ions could be detected. However, after the source had been heated to 1000°C for several minutes and then allowed to return to room temperature, the counting rate increased. It was found that a retarding potential of 50 to 100 volts on grid G_1 reduced the counting rate to the background value. The closing of the steel gate produced the same result.

Figure 2 represents one of the first retarding potential curves obtained for the recoil nuclei. Both grids were at ground potential and the voltage was applied between the source and the nearest grid. It is evident from these data that the recoils have a maximum energy of about 50 electron volts. A potential of 300 volts is sufficient to produce a saturation current of recoil ions.

A considerable gain in intensity was obtained by first accelerating the recoils from the source to grid G_1 by a potential of 100 volts or more. The retarding potential was placed between grids G_1 and G_2. Since the recoil ions have so little energy, it was expected that the counting rate would depend upon the heat treatment of the source. Figure 3 shows this variation of the counting rate. The recoil ions were accelerated from the source to grid G_1 by 176 volts and then retarded by 176 volts plus an adjustable retarding voltage. The data for curve A were taken about one hour after a short heating of the source, whereas that for curve B was taken about one hour after these data. Curve A cuts the background line at about 47 volts and curve B cuts it at 41 volts. Apparently sufficient gas has been adsorbed on the source to reduce the energy of the ions by about 6 electron volts.

As a result of a number of measurements of the decrease in the counting rate as a function of time, it was determined that the rate decreased to one-half the original value in forty minutes. This decrease appeared to be a linear function of the time if the measurements were made ten minutes or more after the heating of the source. The dotted curve just above curve A represents the correction to A if we assume that the decrease in the counting rate due to the adsorption of gas on the source was a linear function of the time. The correction raises the maximum of the recoil energy to 48 electron volts.

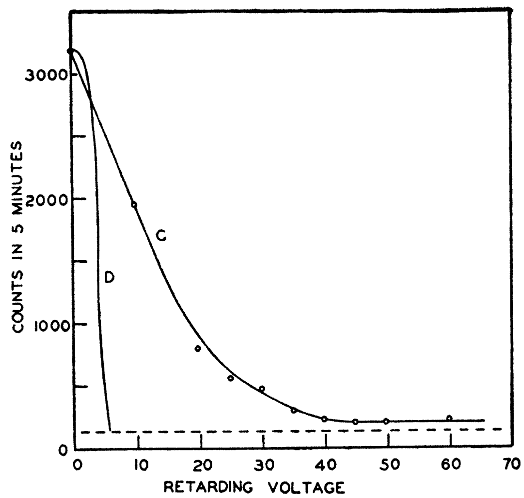

FIG. 4. Curve C is a retarding potential curve for recoil ions whereas curve D is for positive ions emitted from a hot platinum filament. The background counting rate is represented by the dotted line.

The horizontal dotted line represents the counting rate when the steel gate was closed. The small increase in the counting rate with the gate open and the retarding potential greater than 50 volts is due probably to neutral recoil atoms. The fact that this effect varies with the heat treatment of the source rules out either negative electrons or positrons since these should have no difficulty in penetrating the gas layer. These data indicate that Be^7 emits extremely few, if any, positive or negative electrons since positrons of almost any energy and negative electrons having energies greater than 3.6 kev would have been detected.

Figure 4 represents data taken a short time after the source had been heated for several minutes to a temperature of 800 to 900°C. The counting rate was considerably higher than that for curves A and B. In order to test the accuracy of the retarding potential measurements, the radioactive source was replaced with a strip of platinum foil which had been treated with a small quantity of LiF in the same manner as the radioactive source. A copious emission of positive ions was obtained when the strip was heated to a few hundred degrees C. No emission was noticed at room temperature. Curve D represents the data for these ions. The fact that the ions cut the axis at 6 volts retarding potential can be explained by the penetration through grid G_2 of the strong electric field from the first electrode of the multiplier tube. Thus the observed values of the retarding potentials for the recoils should be decreased by 6 volts.

Although the recoil nuclei appear to have a maximum energy greater than the 15.6 electron volts predicted assuming that they are due to the recoil of the 0.45-Mev gamma-ray, the possibility remained that for some unexplained reason they were, after all, due to this gamma-ray. There remained the additional possibility that the recoils were due to the emission of a 0.87-Mev gamma-ray during the Be^7 disintegration. Although Maier-Leibnitz[7] failed to detect gamma-rays of this energy in a cloud-chamber experiment, it was deemed advisable to test whether or not gamma-rays were accompanying the observed recoils. In order to investigate these possibilities the coincidence experiments to be described in the next section were carried out.

COINCIDENCE COUNTING

The resolving time of the coincidence circuits was determined by removing the G-M tube to one side and adjusting the position of a gamma-ray source so that the counting rate was nearly equal to that observed in the actual experiment. The multiplier tube counting rate was produced by an alpha-particle source. This counting rate also was approximately equal to that observed in the experiment. A resolving time of $3.95 \pm 0.22 \times 10^{-7}$ min. was observed.

In order to predict the number of coincidences to be observed if the recoils were due to a gamma-ray, it was necessary to have at least an approximate value of the efficiencies of both tubes. Since it was impossible to measure directly the efficiency of the multiplier tube for 3- to 4-kev positive ions, measurements were made for alpha-particles. A comparison was made between the counting rate obtained with either the multiplier tube or a parallel plate ionization chamber placed over the same slit system. An ionium source was used. This emits alpha-particles having a range of about 2.8 cm of air. The range was reduced to about 1.4 cm by a mica foil. It was found that the counting rates were the same. This indicates that the multiplier tube records every alpha-particle that hits the first electrode. There is reason to expect that the efficiency for the counting of slow positive ions is likewise about 100 percent.

Since the G-M tube subtended a larger solid angle at the source than did the first electrode of the multiplier tube, every recoil produced by a gamma-ray and recorded by the multiplier tube should be accompanied by the passage of the gamma-ray through the G-M counter. Of course, this assumes that the recoil nucleus and gamma-ray go off in opposite directions. The data of Von Droste[8] and Dunworth[9] give the absolute efficiency of a G-M tube similar to that used in this experiment as about two percent for 1000-kev and one percent for 500-kev gamma-rays. Assuming that the efficiency of the tube used in this experiment was of the same magnitude, one finds that the coincidences to be expected for gamma-ray recoils would be about one or two percent of the multiplier tube counting rate.

In the actual coincidence experiment the G-M tube was placed in the position shown in Fig. 1. The G-M tube rate was 190 counts per minute. The multiplier tube counting rate varied from about 200 to 5000 counts per minute depending upon the heat treatment of the source. Coincidences were recorded during either one-half or one-hour intervals. The multiplier tube rate was taken to be the average of readings taken just before and after the coincidence readings. The number of chance coincidences to be expected was calculated from the relation,

$$A = 2\tau N_1 N_2,$$

where A is the number of accidentals per minute, τ is the resolving time in minutes, and N_1 and N_2 are, respectively, the counting rates of the G-M tube and the electron multiplier tube. A typical set of data is given: $N_1 = 190$ counts per minute,

[7] H. Maier-Leibnitz, Naturwiss. **37**, 614 (1938).

[8] G. Von Droste, Zeits. f. Physik **100**, 529 (1936).

[9] J. V. Dunworth, Rev. Sci. Inst. **11**, 167 (1940).

$N_2=605$ counts per minute, total time $=60$ minutes. In this time interval 5 coincidences were observed. The expected number of chance coincidences was 5.7. In all, 50 coincidences were recorded in 12.55 hours. The number of chance coincidences to be expected in this same time was 63.1 ± 5.3.

The number of coincidences to be expected if the recoils were due to a gamma-ray was determined by assuming that the efficiency of the multiplier tube was 100 percent and that of the G-M tube was one percent. Since both counters subtended about the same solid angle at the source, the number of coincidences per minute was given by 0.01 N_2. In the example above, 333 coincidences per hour should have been observed if the recoils were due to gamma-rays. By similar calculations 3757 coincidences should have been observed during the 12.55 hours while actually 50 were observed. The calculated value is about 80 times the observed number of coincidences. This large difference between the observed and expected coincidence rates rules out the possibility of the recoils being caused by either a 0.45-Mev or a 0.87-Mev gamma-ray. Even though the efficiencies of either tube were considerably smaller than the values assumed, some increase in the coincidence rate over that expected by chance should have been observed.

DISCUSSION

An accurate determination of the maximum recoil energy is made difficult by the fact that the retarding potential curves do not approach the axis very steeply. However, this behavior probably is an inherent difficulty in this type of experiment. Since the recoils have so little energy, it is almost impossible to prepare a target that is truly thin. The fact that the observed maximum recoil energy increased when readings were taken immediately after the heating of the target suggests that the true maximum may be somewhat higher than the observed value. An experiment carried out with the target held at a temperature of several hundred degrees C should remove this difficulty.

The momentum of the recoil nucleus ejected by the emission of a neutrino in the Be^7 decay process is given by

$$p=(1/c)(T^2+mc^2T)^{\frac{1}{2}},$$

where p is the recoil momentum, and m and T, respectively, are the rest mass and kinetic energy of the neutrino. Since the neutrino receives most of the energy, T is very nearly equal to 0.87 Mev. If the rest mass of the neutrino is assumed to be zero, the maximum energy of the recoils is found to be 58 electron volts. Both the Fermi and Konopinski-Uhlenbeck theories for the shape of the continuous beta-ray spectrum require the neutrino rest mass to be zero or, at most, 0.2 that of the electron in order to agree with the observed shape of the high energy part of the curve. A neutrino rest mass of 0.2 that of the electron will lower the maximum recoil energy by only one electron volt. Thus the recoil energy must be measured very accurately for a determination of the neutrino rest mass. Since positive ion work functions may be several electron volts for metals not completely outgassed, the observed recoil energy will be a few electron volts less than the actual value. The value observed in this experiment is from 10 to 15 electron volts lower than the expected value. Part of this discrepancy is due to the positive ion work function of the platinum strip and part is due to the energy lost by the ions in penetrating the layer of gas on the surface of the source.

The fact that no positrons were found confirms the observations of Haxby[5] and collaborators on the Be^7-Li^7 mass difference. The value of 1.02 Mev required for positron emission is considerably higher than the value of 0.87 ± 0.03 Mev given by this group.

It has been shown that the observed recoils were not caused by gamma-rays. Unless some new mechanism for the removal of the energy produced in the Be^7 decay process can be discovered, it must be concluded that the recoils were caused by the emission of a neutrino of nearly zero rest mass.

In conclusion, the author wishes to express his gratitude to Professor S. K. Allison of the University of Chicago for suggesting the use of Be^7 in this experiment and also for many helpful discussions during the experiment. Thanks are also extended Dr. Louis Slotin and the other members of the University of Chicago cyclotron crew for preparing the radioactive material used in this experiment.