Momentum Conservation in the Beta-Decay of P^{32} and the Angular Correlation of Neutrinos with Electrons

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It is possible, by evaporation of carrier free P^{32}, to produce what appear to be monolayer beta-active sources. These sources maintain their characteristics for several hours in a good vacuum. The momentum of the recoil ion is measured by timing its flight in a field-free space. Recoil momentum spectra are observed at 180°, 135°, 90°, and 45° with respect to the electrons. It is shown that (a) momentum is not conserved between the electron and the recoil nucleus, (b) the experimental data are in disagreement with any hypothesis in which the neutrino and the electron are most probably emitted in the same hemisphere, (c) for recoil ions above about 25 ev energy, the observed recoil momentum spectra agree rather well with those spectra calculated on the assumption of a $(1-\beta\cos\theta)$ neutrino-electron angular correlation function, and (d) below 25 ev too many recoils are observed compared to any neutrino theory which gives agreement for high momentum recoils. Since the reason for the disagreement below 25 ev is not understood, the selection of the $(1-\beta\cos\theta)$ function must be regarded as tentative.

I. INTRODUCTION

IT has been known for a long time that energy is not conserved in beta-decay if only the beta-particle and the nucleus are considered. A number of experiments have been performed to see if momentum is also not conserved between the beta-particle and the recoil nucleus. Leipunski,[1] Crane and Halpern,[2] Allen,[3] Jacobsen,[4] Wright,[5] and Fowler, Lauritsen *et al.*[6] all report with different degrees of certainty that momentum is in fact not conserved between the beta-particle and the nucleus. A point of particular interest in momentum measurements is whether the experimental results can be interpreted by assuming the existence of a neutrino whose direction has some definite angular correlation with the direction of the beta-particle. The various formulations of Fermi's beta-decay theory[7] predict different angular correlations between the beta-particle and the neutrino.

The experiments referred to above are about equally divided between employing a radioactive gas, or using a thin radioactive deposit on a surface as the source of the beta-particles and the recoils. It is now possible to obtain carrier free, radioactive P^{32} from Clinton Laboratories. This material is so free from even inert contamination (0.6 to 3 milligrams of non-volatile matter per millicurie) that it greatly increases the possibility of forming a true monolayer surface. If a monolayer, or less, can be formed by evaporation in a high vacuum, for example, one might hope that the most serious difficulty encountered in the use of the thin surface radioactive source, namely, scattering and energy loss of the recoils at the surface, can be greatly reduced.

II. THE PRINCIPLE OF THE EXPERIMENTAL METHOD

The principle involved in the experiments about to be described is to measure the momentum of the recoil nucleus by measuring its time of flight in a field-free space. Zero time is taken to be the time at which an electron, going in a selected direction, is detected. An electron multiplier detects the recoil nucleus, also going in some selected direction, at a later time. Since the mass of the recoil nucleus is known, it is possible to calculate the magnitude of its momentum from its measured time of flight. It presumably escapes from the monolayer source with small change of either energy or momentum. A cathode-ray tube displays a horizontal sweep starting whenever an electron is detected. The recoil nucleus, when detected, causes a vertical deflection which can be recorded either visually or photographically. The cathode-ray tube display permits a wide range of the recoil momen-

[1] A. I. Leipunski, Proc. Camb. Phil. Soc. 32, 301 (1936).
[2] H. R. Crane and J. Halpern, Phys. Rev. 53, 789 (1938); 56, 232 (1939).
[3] J. S. Allen, Phys. Rev. 61, 689 (1942).
[4] J. C. Jacobsen and O. Kofoed-Hansen, Mat. Fys. Medd. 23, Nr. 12 (1945).
[5] B. T. Wright, Phys. Rev. 71, 839 (1947).
[6] R. F. Christy, E. R. Cohen, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. 72, 698 (1947).
[7] D. R. Hamilton, Phys. Rev. 71, 456 (1947).

tum spectrum to be measured at one time. This is important because of the limited time (about 2 hours) that the monolayer surface maintains its characteristics.

Only charged recoil atoms can be given acceleration so that they will produce secondary electrons on the first dynode of the electron multiplier. Therefore an electron emitter, P^{32}, was chosen as the radioactive material. It is also free from any gamma-rays whose momenta can complicate matters. The singly-charged positive recoil ion, S^{32}, has a first ionization potential of 10.3 volts. It is necessary to use a surface whose work function is the order of 10 volts as the base upon which the P^{32} is evaporated so the positive S^{32} ions have a chance to escape without first being neutralized.

Since the recoil atoms are charged, care must be taken to give them a field-free space in which to travel before they are detected. Otherwise their direction and energy will be completely altered.

P^{32} has a calculated maximum recoil energy of 78-electron volts. It is hoped that surface binding energy will not seriously affect at least the higher momentum recoils. Barton[8] found that an appreciable fraction of RaE recoils, whose energy is the order of 1 ev, were able to escape from a surface.

III. DESCRIPTION OF THE APPARATUS

Figure 1 shows the measuring chamber used in the experiments. A thin mica sheet, S (1 to 1.5 mg/cm^2), has on it the evaporated radioactive surface. The total activity is usually about 1 to 3×10^4 electron per second. The size of the surface is about 1 cm by 0.6 cm. This surface is prepared in an adjoining evaporation chamber, as shown in Fig. 2. The details of the preparation of the surface will be discussed in the next section.

After its formation the surface S is moved to the measuring chamber through the magnetically operated valve, C. Both chambers are maintained by separate pumps at a pressure between 1 and 3 times 10^{-7} mm of Hg, so that from the time of its formation, the surface is in a vacuum.

The inside of the measurement chamber is covered with a grounded beryllium film. There is a grounded grid in front of the electron multiplier made of 0.0025-cm tungsten wire knitted into a mesh with an average hole size of about 0.06 cm. This permits about 80 percent transmission. The Geiger counter ports, Fig. 1, are also protected by a similar grounded grid. Thus no external field can penetrate the space surrounding the source.

The electron multiplier is a 12-stage, beryllium-coated unit following the design of J. S. Allen.[9] It is outgassed by induction heating after each exposure to air to obtain maximum gain (50,000 to 100,000). It is followed by feed-back amplifiers with a total voltage gain of about 10^6, and a rise time of 0.1 microsecond.

The cathode-ray tube sweep, which starts upon the detection of the electron in the Geiger counter, is 15 microseconds long. It is calibrated by a one megacycle shock-excited oscillator. An edge lighted scale marked in one-half microsecond divisions is used to read the time of occurrence of the pulses from the recoil ions. The source is usually weak enough so that the recoils come at a convenient rate for recording by visual observation. The slight persistance of the type P1 screen aids greatly in this. The fact that results on a given source can be reproduced to within limits set by statistics indicated that this method of data collection does not contribute greatly to the error. When stronger sources with the necessary monolayer characteristics can

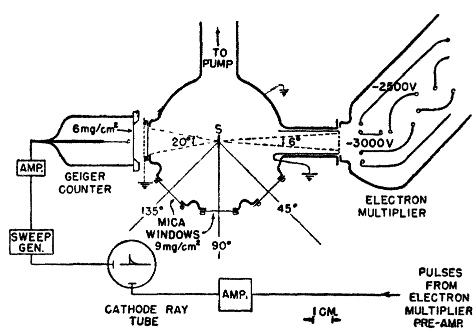

FIG. 1. Horizontal cross section of the measurement chamber. The monolayer P^{32} source is on S, facing the electron multiplier which detects the positive (sulfur) recoil ions. The electrons are detected by the Geiger counter which can be placed in front of any one of the four mica windows. Measurement of the time of flight of each recoil ion permits a calculation of its momentum. The field-free path of the recoil ions is 6.5 cm.

[8] A. W. Barton, Phil. Mag. 1, 835 (1926).

[9] J. S. Allen, Rev. Sci. Inst. 12, 582 (1941).

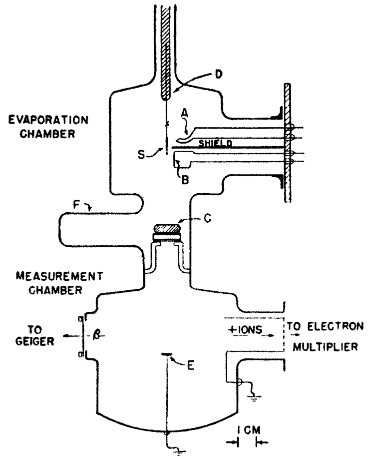

FIG. 2. Vertical cross section of the complete vacuum system. The source S can be raised, lowered, or rotated by the rod D which is magnetically controlled. S is first coated with LiF (or SiO_2) evaporated from a platinum filament A (or a tungsten coil at A). It is then lowered and coated with P^{32} from the platinum filament B. Gate C is opened magnetically, and S is lowered to E where it rests while observations are made.

be formed, a recording camera will be used to collect the data.

The mica windows fastened on with Dennison's American Express No. 2 red wax. A glass ring on the outside of the mica is also waxed to the mica, thus holding it from both sides. A copper washer with the edges rounded is placed in between the mica and the ground-glass port on the vacuum system. The rounded edges reduce danger of cracking in the mica as it bows inward under the pressure of the atmosphere.

Typical sets of data collected with this apparatus are shown in Fig. 3, and the momentum spectra of these recoils are shown in curves A of Fig. 4. The significance of this data will be discussed in a later section.

IV. PREPARATION OF THE MONOLAYER SOURCE

The production of a true monolayer source which causes a minimum of scattering of both electrons and recoil ions is the most critical part of this type of experiment. In previous experiments the thin radioactive sources used have probably not been monolayers. It might be expected that the evidence of energy loss and scattering of recoils present in these previous experiments, notably Allen's,[3] would be missing when large quantities of high activity carrier-free materials are available to form true monolayers. Proof that monolayer sources were actually formed in the experiments reported here is mostly indirect. It is deduced from the appearance of the recoil momentum spectra. However, the contamination of the radioactive material before evaporation was so low that a further purification during evaporation of a factor of 10 to 100 will produce monolayers of adequate activity.

First, a mica sheet (1 to 1.5 mg/cm^2) is coated in an auxillary vacuum system with a thin beryllium layer. In operation, this layer is grounded. The reason for this is to remove the effects resulting from electrostatic charge caused by the electrons leaving the radioactive surface. Some early measurements were in error because of this electrostatic charge. The mica plus beryllium surface is then placed in the evaporation chamber, Fig. 2, where it is further processed.

Since the sulfur recoil atoms have a first ionization potential of 10.3 volts, and since their velocities are low (order of 10^6 cm/sec.), they have small probability of escaping in a charged condition from a surface unless the work function of that surface is in the neighborhood of 10 volts. No metals have this high work function, and no charged recoils were observed to come from surfaces of Al, Be, and W, for example. A search was made for easily evaporated insulators which might have the electrons of the surface atoms strongly enough bound so that the recoil ions could escape charged. Freshly evaporated surfaces of SiO_2, LiF, and NaF were found to permit a measurable number, probably less than 10 percent, of the recoil ions to escape charged. Therefore in the evaporation chamber, Fig. 2, the first step is to evaporate an insulating film, a few wave-lengths of light in thickness, on top of the beryllium surface of S. A shield prevents this evaporating material from contaminating the platinum filament, B, on which some P^{32} is deposited.

The method of preparing the radioactive deposit on filament B, Fig. 2, will now be described. The P^{32} is obtained from the Clinton Laboratories in a pH 7.5 solution containing 10 millicuries of phosphorus in the form of $NaHPO_4$.

The non-volatile matter varied from 0.6 mg/mc up to 2 or 3 mg/mc. The nature of this non-volatile matter was unknown in all cases, and it appeared to vary from shipment to shipment since the evaporation characteristics of the P^{32} were quite different in different shipments.

To the original radioactive solution HCl is added until the pH is 3 or 4. Then 25 micrograms of $FeCl_3$ in solution is added, followed by the addition of NH_4OH. The solution is heated, to aid coagulation, and centrifuged. Usually, about 70 percent of the activity goes with the precipitate. This is washed and dissolved in 0.1 N HCl. Sometimes the material is re-precipitated several times without the addition of more $FeCl_3$. The phosphorus is presumably in the form of iron phosphate.

The next step is to calibrate the evaporation characteristics of the iron phosphate solution from the center of a standard platinum filament, 0.002 inch thick, 0.082 inch wide, and about 1.5 inch long. This calibration is done in terms of the current through the filament so that the temperature conditions can be easily and accurately reproduced.

About 0.1 millicurie of solution is evaporated to dryness in air on a clean platinum filament. This filament has been cleaned by previous heating in a vacuum to just below the melting point. The loaded filament is placed in an auxillary vacuum system having a mica window in front of the active deposit on the filament. A Geiger counter measures the activity of the filament as a function of the heat treatment. A magnetically operated shutter prevents the radioactive material from depositing on the mica window during evaporation. In the best case, 80 percent of the original activity of the filament disappeared after two or three minutes heating in the temperature range of 1000°C to 1120°C. Usually it required a temperature range of 750°C to 1180°C. Measurements on different filaments loaded with radioactive P^{32} from a given solution showed very reproducible evaporation characteristics.

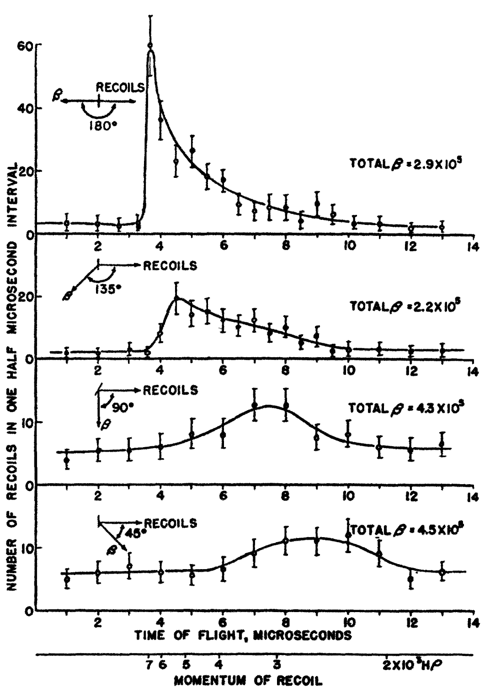

FIG. 3. Typical time of flight diagrams for the recoil ions from P^{32}. The radioactive source has a foundation layer of LiF upon which the thin layer of P^{32} is deposited by a double evaporation process. The recoil-momentum spectra, corresponding to these diagrams, are shown in curves A of Fig. 4. The geometry of the detection system is shown in Fig. 1. "Total β" means the total number of electrons detected while the data were being collected.

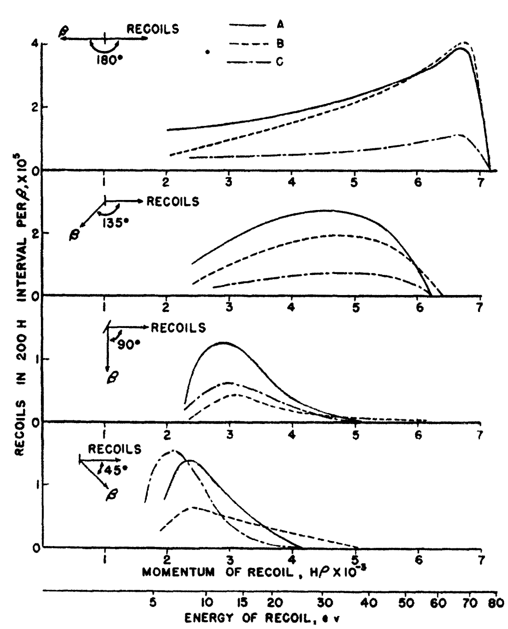

FIG. 4. Some momentum spectra of recoil ions from P^{32}. For A, the base surface is LiF with the P^{32} deposited by a double evaporation process. For B, the base surface is LiF with the P^{32} deposited by a single evaporation. For C, the base is SiO_2, with the P^{32} deposited by a single evaporation. *Note:* The symbol ρ should follow the letter H in the label of the abscissa.

Once the evaporation characteristics of a given solution of P^{32} is known, the filament, B, in Fig. 2 is loaded with about 0.1 mc, and the filament (or coil) at A is charged with the insulator to be used to form the base surface. When the pressure is low enough (2×10^{-7} mm of Hg), the insulator is evaporated on to the surface S. With S protected by the shield, filament B is heated in exactly the same sequence as the test sample. At the selected point in the evaporation curve, the surface S is lowered so it is exposed to B. B is then heated to some higher temperature for about 30 or 40 seconds, and then turned off. When a single evaporation process is performed in the manner described, it is usually necessary to make several trials to find the region on the evaporation characteristic curve which gives good sources.

After the evaporation process is completed, the surface S is lowered into the measurement chamber, a process which takes about one minute. It takes several more minutes to collect enough data to determine the general characteristics of the recoil spectrum, but there is no evidence of any change in the recoil spectrum for a period of one or two hours providing the pressure is 1 or 2 times 10^{-7} mm of Hg. The ground-glass gate, C, can be left open after the evaporation process is completed without contaminating the measurement chamber. No radioactivity is found in the liquid air cooled traps on the pumps.

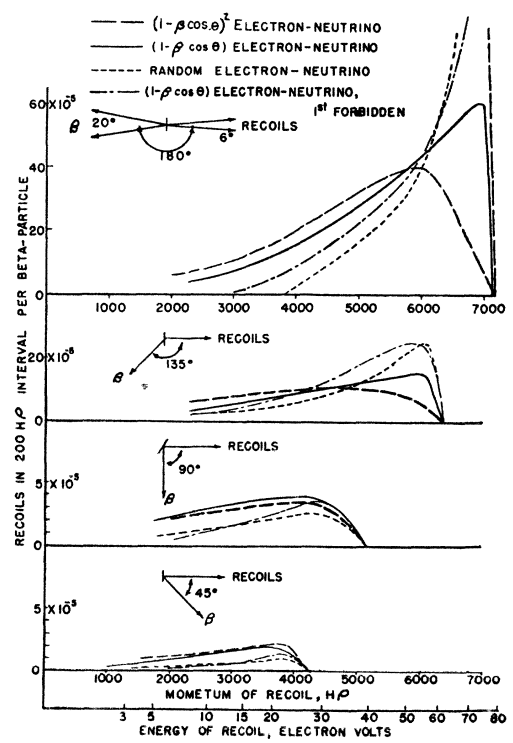

FIG. 5. Theoretical recoil momentum spectra based on the neutrino hypothesis. The geometry of the detection system is shown in Fig. 1. The 180° random neutrino peak is at 360×10^{-5} and the $(1-\beta\cos\theta)$ first forbidden peak is at 135×10^{-5}.

When the evaporation curve has poor characteristics, i.e., wide temperature range necessary to cause the majority of activity to disappear, a double evaporation process is used. A clean platinum filament is used in an auxillary vacuum system as a "catcher." It intercepts the evaporating radioactive material from a heated filament. The "catcher" is exposed only during the most favorable evaporation region of the heated filament (1000°C to 1200°C). The "catcher" has no visible deposit. Not even interference fringes are visible. It has an activity of about 1/20 or 1/40 millicurie. The evaporation characteristics of the "catcher" are now measured in the auxiliary system. It is found that 80 percent of the activity disappears at a much lower temperature (between 640°C and 940°C) than was the case for the original material. This probably means that the P^{32} deposit on the "catcher" has a different chemical form than it had before the first evaporation. A freshly prepared "catcher" is placed in the regular evaporation chamber, Fig. 2. It is found to give good and consistent results in preparing what appear to be monolayer sources on the surface S if S is exposed during the favorable evaporation region (640°C to 900°C) of the "catcher."

V. DESCRIPTION OF SOME TYPICAL DATA

Figure 3 shows a typical set of time of flight data. The data was collected in time intervals ranging from $\frac{1}{4}$ microsecond to one microsecond, but in the diagram all points are normalized to the number in a $\frac{1}{2}$-microsecond interval. Short time of flight corresponds to high momentum, as can be seen from the momentum scale in Fig. 3. The total number of beta-particles detected during the observation time for each curve is noted on the diagrams. Observation time per curve varied from about 15 to 45 minutes.

The pulses observed from 0 to 3.5 microseconds are the random background. These pulses are partly due to recoils unrelated to the particular electron which started the sweep, and partly due to electrons. The electron multiplier is about 5 or 10 percent as efficient as a Geiger counter for P^{32} electrons.

It is a straightforward calculation to change the time of flight diagram of Fig. 3 into the momentum diagram, curve A, Fig. 4. The non-linear relation between time of flight and momentum makes the sharp peak of the 180° case in Fig. 3 to be greatly attenuated in Fig. 4. The momentum diagrams are plotted in terms of recoils in a $200H\rho$ interval per electron. This is the form in which the theoretical momentum diagrams, based on the assumption of the existence of the neutrino, are presented in Fig. 5.

The delays in the measuring system are small and constant. After the recoil passes the grid in front of the electron multiplier, it is calculated that the ions take a nearly constant time of 0.46 microsecond to be accelerated and to reach the sensitive region of the first dynode. From there on, the pulse from the ion is delayed only by the amplifier which has a rise time of about 0.1 microsecond and a voltage gain of about 10^6.

Delays in the Geiger counter have been measured,[10] and found to be the order of 0.1 microsecond.

When data are collected in tenth microsecond intervals, a number of recoils are observed to have the maximum energy of 78 ev, which corresponds to a 3.5-microsecond time of flight. This maximum energy is calculated from the known maximum electron momentum of $7200H\rho$. The experimental error in this measurement is estimated at ± 0.2 microsecond, or ± 8 ev. Recoils are observed out to 14 microseconds, corresponding to an energy of 5 ev.

VI. A DISCUSSION OF SOME ERRORS

Some consideration will now be given to the sources of errors which can affect the shape of the recoil momentum spectra.

It has been assumed up to now that the observed delayed pulses are really due to mass

[10] C. W. Sherwin, Phys. Rev. 71, 479 (1947).

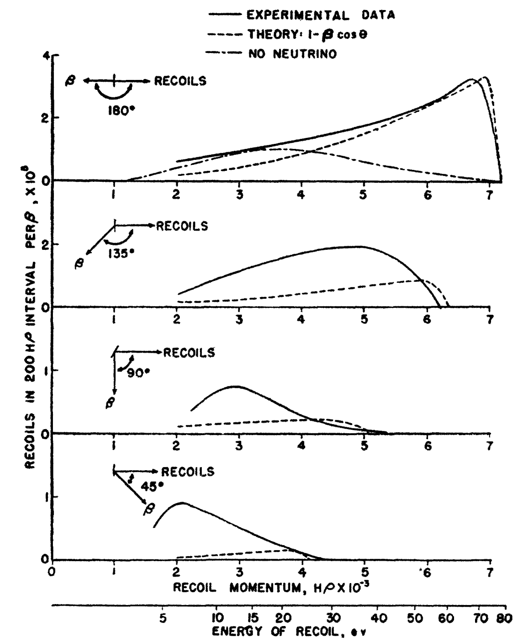

FIG. 6. Comparison of experimental data with the $(1-\beta\cos\theta)$. neutrino hypothesis. This neutrino-electron angular correlation function is predicted by the scalar and pseudoscalar forms of beta-interaction. The experimental data are the average of four different runs, including the three shown in Fig. 4. The curve for the case of "no neutrino" is identical in form to the electron spectrum, since in this case the electron and the recoil nucleus always have equal and opposite momentum. All the curves calculated on the assumption of the $(1-\beta\cos\theta)$ neutrino-electron correlation function shown in Fig. 5 have been divided by 18.5 before plotting them in Fig. 6. This normalizes the amplitudes of the theoretical and experimental curves for the 180° case.

32 ions. This assumption was confirmed by measuring the mass of these ions in the following manner. A grounded grid was placed 2 or 3 millimeters in front of the surface S, Fig. 1. The conducting layer of surface S was then placed at a positive potential of 100 volts. Upon reaching the grid, the ions have a total energy of $(E+100)$ ev, where E is their initial energy, if, as is assumed, they are singly charged. The new minimum time of flight was measured as 2.3 microseconds. If one assumes that the mass of the ion is 32 (0.532×10^{-22} gram) and that its initial energy is about 80 ev, one predicts a minimum time of flight of 2.4 microseconds. This mass measurement is accurate to only about ± 30 percent mainly because of the short time intervals involved, but the possibility that some spurious effect was producing ions of a different mass is ruled out.

There is the possibility that electrostatic charges on the radioactive surface will cause errors. In fact, before the conducting grounded surface was added to the mica, an electrostatic potential, constantly increasing at about 10 or 20 volts per hour appeared on the surface. This was due to the negative beta-particles leaving. Since few charged recoils escape, a positive charge collects on the active surface. This causes a gradual speeding up of all the recoil ions in a direction normal to the surface *S*. In one case a potential of about 500 volts was observed 36 hours after the radioactive surface was formed. This effect was completely removed after the conducting, grounded, beryllium film was added to *S*, because of the greatly increased electrostatic capacity of the radioactive layer with respect to ground. The extreme thinness of the insulating layer of SiO_2 or LiF makes this capacity of the order of several thousand centimeters compared to a capacity of the order of 1 centimeter when no conducting film is present.

There is the possibility that the chemical nature of the foundation surface on which the P^{32} layer is deposited may effect the recoil momentum spectra. Good agreement on a number of runs with SiO_2, LiF, and NaF as the foundation surfaces reduces this possibility.

Related to the above point, there is the possibility that the positive ion "neutralization efficiency" of the surface will have an effect on the recoil spectra. The number of recoils in a given time of flight interval per electron detected varied by over a factor of 4 without changing the shape or the relative amplitude of the recoil momentum curves in any appreciable way. On the average, LiF permits about two or three times as many recoils to escape charged as does quartz. NaF was less efficient than quartz, and for that reason the data on it are very limited.

There is the possibility that the contaminating material evaporated with the P^{32} will cause some sort of selective effect on the escape of the recoil ions. This source of error is reduced by the fact that P^{32} deposits from different shipments from the Clinton Laboratories, on the platinum filament, have rather different evaporation characteristics. This indicates that there are different amounts, and probably different kinds of inert contamination materials. The recoil spectra are very similar. Furthermore, the double evaporation process in which the second evaporation occurs at a much lower temperature than the first evaporation gives the same recoil spectra.

There is the possibility that the orientation of the path of the recoils with respect to the normal to surface *S*, Fig. 1, will affect the recoil spectrum. In most of the measurements the surface *S* was oriented approximately normal to the line between the surface and the electron multiplier. An exception to this is the case where the electron-recoil angle is 90°. Here the surface (Fig. 1) is rotated about an axis normal to the paper through about 30°, so that the electrons can get to the Geiger counter without passing through the mica backing of the surface *S*. Some experiments were done at 180° to test the effect on the recoil spectrum of the orientation of the surface *S* with respect to the recoils. The surface was rotated about a vertical axis through 45° with respect to its position in Fig. 1. This caused about a 30 percent decrease in the intensity of the recoil momentum spectrum, but practically no change in its shape. This means that the recoil spectrum is substantially independent of the orientation of the direction of the recoils with respect to the normal to the surface over a range of about ±45°. It also means that as a recoil makes a larger and larger angle with the normal, its probability of escaping, at least in a charged state, decreases. However, this decrease in escape probability seems to be about the same for all recoil momenta. This strengthens the arguments presented above that the surface does not selectively neutralize the recoil ions, thus distorting their momentum spectra.

Scattering of the electrons is a possible source of error. The backing on the source *S* has a thickness of 1 to 2 mg/cm², and this can cause the low energy electrons below about $1000H\rho$ to be strongly absorbed and scattered. However, the 15 mg/cm² mica windows that the electrons must penetrate to be detected cut out all electrons below $1{,}200H\rho$, and strongly absorb them up to still higher values of $H\rho$. To check the order of magnitude of the effect of *S* upon the electrons, a source of 1.4 mg/cm² thickness is mounted in its standard 0.009-cm diameter copper wire cradle a distance of about 6 cm from the Geiger counter. The active surface was alternately faced toward, and away from the Geiger counter, with a total absorber of 15 mg/cm^2 in front of the Geiger counter. A total of about 2 percent difference in counting rate was observed. About half of this was accounted for by the shielding resulting from the wire cradle. Thus, at most, only a few percent of the electrons are affected by the backing material of the source.

The reproducibility of the data was rather good. Out of about 35 surfaces, 15 gave no usable data. Either no recoils escaped at all, or there were too few to get any data. This was probably due to some contaminating material covering up the radioactive surface. For five or six surfaces, instead of the typical 180° recoil spectra in Fig. 4, an excessively large number of low momentum recoil ions were observed. It is inferred that these surfaces were thicker than a monolayer. As a "good" surface slowly becomes contaminated in the vacuum, the number of low momentum recoils increases so that the spectrum is very similar to a "thick" layer spectrum. Also, the intensity of recoils diminishes as the originally good surface becomes contaminated. Four surfaces, including the three shown in Fig. 4, had fairly good statistics for all four angles, and agree fairly well with each other regarding the shape and relative amplitudes of the various curves in the high momentum region. In addition, 10 surfaces with poorer statistics agree with the data of Fig. 4.

A particularly important point is the reproducibility of the 180° curve. When cases having deviations from the typical runs were observed, they invariably had fewer high momentum recoil ions, and more low momentum recoil ions. This fact, coupled with the known purity of the original radioactive material, supports the assumption that the reproducible cases are due to true monolayers, or less, of P^{32}.

VII. COMPARISON OF RESULTS WITH NEUTRINO THEORY

Figure 5 shows the theoretical recoil momentum spectra for P^{32} calculated with the following assumptions:

(a) A neutrino, whose rest mass is small compared to the rest mass of the electron, is assumed to leave the nucleus in the beta-decay process. (b) The neutrino and the electron share the available energy of 1.72 Mev. The energy carried away by the nucleus is negligible. (c) Four different assumptions are made about the neutrino-electron angular correlation function:

1. The random neutrino. It is assumed that the probability of the neutrino entering the element of solid angle $d\Omega$ is $1/4\pi d\Omega$. In this case all elements of solid angle are equally probable, independent of the direction of the electron. If θ is the direction between the neutrino and the electron, and the solid angle element is $2\pi \sin\theta d\theta$, then the above expression becomes $(\frac{1}{2}) \sin\theta d\theta$. This is the probability that the neutrino makes an angle θ with the electron, and enters an angle element, $d\theta$. Thus for the random neutrino the most probable direction is 90° with respect to the direction of the electron. This function is similar to those predicted by the tensor and axial vector forms of beta-interaction for an allowed transition in the Fermi theory.[7]

2. The probability that the neutrino makes an angle θ with respect to the electron and enters a solid angle element $d\Omega$ is $(1/4\pi)(1-\beta\cos\theta)d\Omega$. β is the ratio of the velocity of the electron to the velocity of light.

This function is predicted by both the scalar and pseudoscalar forms of interaction in the Fermi theory for an allowed transition.[7]

The most probable angle between the electron and the neutrino is about 120°.

3. The probability that the neutrino makes an angle θ with respect to the electron and enters a solid angle element $d\Omega$ is

$$\frac{1}{4\pi(p/2q+q/2p-1/3)}(1-\beta\cos\theta)(p/2q+q/2p+\cos\theta)d\Omega.$$

Here p and q are the magnitude of the electron and neutrino momenta, respectively.

This function is predicted for the first forbidden transition when the allowed transition has the correlation function of $(1-\beta\cos\theta)$.[7]

The most probable neutrino-electron angle for this function is 90° for those electrons near the middle of the spectrum. For electrons near either end of the electron spectrum, the most probable angle is near 120°.

4. With no theoretical suggestion, the following neutrino-electron angular correlation function was also used as a basis for calculation:

$$\frac{3}{16\pi}(1-\beta\cos\theta)^2 d\Omega.$$

For this function the most probable angle between the neutrino and the electron is 135°.

No plot is made on Fig. 5 of the correlation function predicted by the polar vector form of the Fermi theory,

$$\frac{1}{4\pi}(1+\beta\cos\theta)d\Omega.$$

Here the most probable angle between neutrino and electron is about 60°. This function gives a peak on the 180°

curve of Fig. 5 which is twice as high as is the peak for the random neutrino.

(d) There is no scattering of either the electrons or recoil ions. (e) The electron momentum spectrum is that measured by Lawson,[11] corrected for the absorption in the mica windows which are 15 mg/cm^2 in thickness. This spectrum is plotted in Fig. 6. (f) One hundred percent efficiency is assumed for the Geiger counter for electrons, and in the electron multiplier for recoil ions of 3000-volts energy.

The calculations plotted in Fig. 5 were done by a geometrical method, using numerical integration.

The disappearance at a definite point of the high momentum recoils for the 135°, 90°, and 45° theoretical spectra in Fig. 5 is characteristic of any neutrino hypothesis applied to the given geometry. This effect can be called the "geometrical cut-off," since the cut-off point varies systematically with the geometry of the detectors and is independent of the neutrino-electron angular correlation function.

The similarity between the experimental curves in Fig. 4 and the theoretical curves in Fig. 5 can be seen in Fig. 6. The average of four different experimental curves and the neutrino theory curves for the $(1-\beta\cos\theta)$ case are plotted in Fig. 6. Here the theoretical curves of Fig. 5 have all been divided by 18.5. This normalizes the peak of the 180° curve to the experimental 180° curve. Although there is fair agreement in the high momentum recoil region, it is apparent that the experimental curves show several times too many recoils in the low momentum region.

Several conclusions can be based on the high momentum regions of the recoil spectra, above 4000-$H\rho$ or 25-ev energy. It is in this region that the data are most reproducible, and where there is least evidence of surface effects.

The "no neutrino" curve drawn in Fig. 6 is identical in form to the electron-momentum spectrum, since in this case the recoil and the electron always have equal and opposite momenta. The great difference between this curve and the experimental curve makes it fairly certain that momentum is not conserved between the electron and the recoil nucleus. The reproducibility of this 180° curve under a variety of conditions is taken as one of the principle supports for this conclusion.

The fact that the experimental curves at 135°, 90°, and 45° show any recoils at all, and that these recoil spectra have about the same upper limit of momentum as that predicted by the neutrino hypothesis, is rather good evidence supporting this hypothesis. That the presence of these recoils and the high momentum "cut-off" effect can be due to the scattering of the recoils at the surface is, of course, a possibility. This would require, however, some very arbitrary assumptions about the dependence of scattering on recoil energy and direction in order to predict the observed facts in a quantitative manner.

The 180° experimental curve clearly favors the $(1-\beta\cos\theta)$ neutrino correlation function. If the large numbers of high momentum recoils predicted by the random neutrino, the $(1-\beta\cos\theta)$ first forbidden, or the $(1+\beta\cos\theta)$ theories were present, they would be very easily observed. For over 20 different surfaces from which recoils were observed, there was never any evidence of such large numbers of high momentum recoils. The failure to observe them may be due to energy losses at the surface causing a broadening of this sharp peak. It is hard to imagine how this broadening of the 180° peak could occur without also producing some scattering of the recoils. That high momentum recoils in the 6400–7200$H\rho$ region are not scattered through angles of even 45° is seen by the disappearance of these recoils in the 135° experimental curve.

It is concluded that the data definitely favor the $(1-\beta\cos\theta)$ neutrino-electron correlation function. This conclusion is only tentative, however, since the discrepancies with this theoretical assumption below 25 ev are very marked, and since the 135° curve does not fit the theory in the 4000- to 5500-$H\rho$ region. In some respects the $(1-\beta\cos\theta)^2$ function agrees as well with experiment as does the $(1-\beta\cos\theta)$ function.

More experiments are needed to positively rule out any of the neutrino-electron angular correlation functions mentioned above, with the exception of the $(1+\beta\cos\theta)$ function. It is difficult to see how the experimental data can be reconciled to this last function.

The region of recoil momentum below 4000$H\rho$ or 25 ev will now be considered.

[11] J. L. Lawson, Phys. Rev. 56, 131 (1939).

First of all, it is not too surprising that peculiar effects occur in this region since the recoil energies begin to approach the chemical binding energies of the surface. In general, the agreement between theory and experiment gets progressively worse toward lower energies, and is worst of all in the 5 to 10 ev region.

An effort was made to see what particular region, if any, of the electron spectrum was causing the low momentum recoil peaks at 90° and 45°. It was observed for several different radioactive surfaces that these peaks were either completely removed, or greatly attenuated if aluminum filters were placed in front of the Geiger counter. For the 90° case, a filter of 136 mg/cm^2 was added to the 15 mg/cm^2 already present. This completely removed the peak. A filter of 68 mg/cm^2 merely removed the high momentum part of the peak. For the 45° case, 68 mg/cm^2 was adequate to greatly attenuate the peak. This shows that the peaks are due principally to the electrons between 1200$H\rho$ (the electron cut-off for 15 mg/cm^2) and three or four thousand $H\rho$. This behavior is predicted by any neutrino hypothesis.

Definite conclusions regarding the apparently anomalous intensity of the recoils below 25-ev energy can be reached only with the aid of further experiments.

It is interesting that ions with an ionization potential of 10.3 volts can escape charged from surfaces of SiO_2, LiF, and NaF. It may be possible to use this technique to investigate the binding energy for electrons on the surfaces of insulators. The use of different beta-active species would widen the range of investigation.

Since the recoil ions are extremely sensitive to any contaminating deposits from the vacuum, this technique may be useful in studying the manner in which freshly prepared surfaces reach equilibrium with low pressure gases.

VIII. CONCLUSIONS

1. There is good evidence that momentum is not conserved between the electron and the recoil nucleus in the beta-decay of P^{32}. This evidence is mainly the shape of the 180° recoil momentum spectrum, the presence of recoils at other angles, and the "geometrical cut-off" of high momentum recoils at other angles.

2. The $(1+\beta\cos\theta)$ function (polar vector interaction) is so strongly in disagreement with the experimental data that it is very probably not a possible neutrino-electron correlation function. It is safe to include in this category any function such as that predicted by the tensor interaction in which the neutrino and the electron most probably go into the same hemisphere.

3. In the region of recoil spectra above about 25 ev, the agreement is fair between the observed spectra and the spectra predicted by a neutrino whose angular correlation with the electron is given by $(1-\beta\cos\theta)$. This function is predicted by both the scalar and pseudoscalar forms of the Fermi theory for allowed spectra. This implies that P^{32} an allowed transition; however, the first forbidden transition can not positively be ruled out. Also, a function which predicts an even more strongly opposite neutrino, such as the $(1-\beta\cos\theta)^2$ function, can not be ruled out.

4. The random neutrino is less probable than those mentioned under 3 above, but it will probably be necessary for more experiments to fix the limits of error before even this case can be definitely discarded.

5. The unexplained difference between theory and experiment below recoil energies of 25 ev is the principle reason for limiting the above conclusions.

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