than that from MsTh and can be specified as 2.531±0.010 Mev.

ACKNOWLEDGMENTS

The author is indebted to Dr. E. Segrè and his group for making these sources available for this work, to Dr. A. Hemmindinger for his collaboration in the work with the Sb-Be source, and to Dr. J. H. Williams for his support and interest in this work.

Note added in Proof.—Peacock and Jones have reported a value of 1.853±0.03 for the energy of the yttrium gamma-ray which is in agreement with the value deduced from the present work (W. C. Peacock and J. W. Jones, Plutonium Project Record CNL14 (February, 1948).

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Neutrinos from P 32

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Sources of P 32 which come close to being true monolayers are prepared by evaporation in a vacuum. The characteristics of these sources are maintained for 5 to 10 days with the aid of radiant heating. Surface charges are neutralized by periodic "baths" of thermal electrons. The momentum of the electrons is measured with a magnetic spectrometer and the momentum of the recoil ions is measured by observing their time of flight in a field free space.

The momentum measurements show that the missing momentum disappears in one package. Separate energy measurements determine the amount of energy which disappears. The observed ratio of the missing energy to the missing momentum is equal to the velocity of light (±20 percent), as required by the hypotheses that one neutrino is emitted in beta-decay.

After experimentally determined corrections are made for the effects of surface scattering of the recoil ions, it is concluded that the missing momentum vector (i.e., the neutrino) most probably enters the same hemisphere as the electron. The experimental points fit best on a curve of the form, $(1+v/c\cos\theta)$. This is in disagreement with previous tentative conclusions by the author which are now shown to be in error due to surface losses and scattering of the recoil ions.

I. INTRODUCTION

In a recent review article, H. R. Crane[1] has described the search for the neutrino through its effect on the parent nucleus during the process of beta-decay. Experiments, performed over the past decade, have conclusively shown that momentum is not conserved in beta-decay, and there is some more or less tentative evidence[2,3] that the neutrino direction is either approximately random, or favors the opposite hemisphere with respect to the electron.

Both Crane[1] and Allen[2] point out that no recoil experiments have yet demonstrated that a single neutrino is emitted in beta-decay. However, in the Fermi theory[4] the bell shaped momentum distribution of the electrons is a consequence of the emission of two fast particles. The main factor which controls the shape of the electron momentum spectrum at high momenta is the number of cells in momentum space that are available to the electron and the neutrino.[5] If there were two neutrinos the electron spectrum would be quite different than observed.[6] Recoil experiments are also capable of giving information on this point, either by observing monoenergetic recoils from K capture as Crane[1] has suggested, or as in the present experiments, observing monoenergetic recoils associated with monoenergetic electrons.

An important objective of these experiments is to determine as much as possible about the angular correlation between the electron and the neutrino. Different forms of the neutrino-electron interaction predict different angular correlations.[7] Also the angular momentum change which determines the "forbiddeness" of the transition should affect the neutrino-electron angular correlation. Hamilton[7] shows that as the forbiddeness increases, the neutrino tends to go more and more in the same direction the electron, this correlation being greatest when the electron and neutrino momenta are equal. This effect can be visualized by the following simple classical picture. There is only a definite amount of energy available for the electron and the neutrino. Consequently, a limited amount of linear momentum can be carried by the two particles. If this linear momentum leaves the

[1] H. R. Crane, Rev. Mod. Phys. **20**, 278 (1948).
[2] James S. Allen, Am. J. Phys. **16**, 451 (1948); Allen, Paneth, and Morrish, Phys. Rev. **75**, 570 (1949).
[3] Chalmers W. Sherwin, Phys. Rev. **73**, 216 (1948); **73**, 1173 (1948).
[4] Enrico Fermi, Zeits. Physik **88**, 161 (1934).
[5] Emil J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
[6] J. Blatt, private communication.
[7] Donald R. Hamilton, Phys. Rev. **71**, 456 (1947).

nucleus at some distance from the center it can produce the required change in angular momentum. When the electron and neutrino have about the same momentum, they must go in the same general direction in order that their total momentum can cause an angular momentum change in the nucleus. Near either end of the electron momentum spectrum, one particle has almost all the momentum, the direction of the other particle no longer appreciably affects their total momentum, and the angular momentum change no longer tends to correlate the direction of the neutrino and the electron.

II. THE PRINCIPLES OF THE EXPERIMENTAL METHOD

Some of the beta-decay recoil experiments performed to date have measured the recoil ion momentum distribution associated with the electrons traveling in a selected direction, but with no selection of the magnitude of the electron momentum.[2,3] The addition of a magnetic deflection beta-spectrometer makes possible the selection of the magnitude as well as the direction of the electron momentum. The direction of the recoil ion can be selected by means of slits, and its velocity determined by measuring its time of flight in a field free space. Thus, the beta-spectrometer and the recoil time of flight spectrometer permit direct measurements of the electron and recoil momentum vectors. If one assumes the conservation of momentum, the neutrino momentum can be immediately inferred by vector subtraction.

The same apparatus permits an independent measurement of the neutrino energy. The beta-spectrograph also specifies the electron energy, so the balance of the available energy can be assigned, assuming the conservation of energy, to the neutrino.

The ratio of the neutrino energy of the neutrino momentum must be equal to the velocity of light

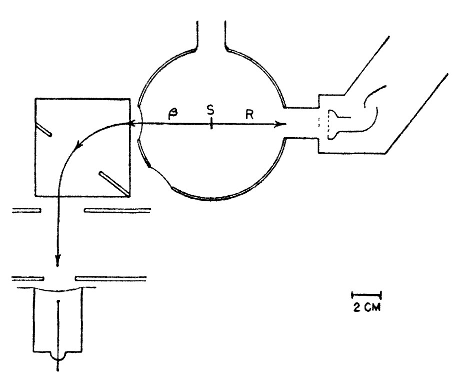

FIG. 1. Apparatus for neutrino recoil measurements. The P 32 source faces the electron multiplier. The velocity of the recoil ions is determined by measuring their time of flight. The momentum of the electrons is measured by the 90° deflection spectrometer.

for all cases where the energy is large compared to the rest mass. Since it requires a neutrino of several hundred thousand electron volts to impart a few electron volts energy to even a light nucleus, and since the rest mass of the neutrino is known to be less than 5 kev,[8,9] recoil experiments are very insensitive to the neutrino rest mass.

A convenient expression for the magnitude of the neutrino momentum, p_ν, is

$$p_\nu/m_ec=(E_0/m_ec^2+1)-((p_e/m_ec)^2+1)^{\frac{1}{2}}, \quad (1)$$

where p_e is the electron momentum in oersted-cm, m_ec is 1700 oersted-cm, m_ec^2 is 0.51 Mev, and E_0 is the upper end point of the electron kinetic energy spectrum in Mev. This expression is obtained using only the conservation of energy and the assumption that the neutrino rest mass is negligible ($p_\nu=E_\nu/c$).

III. A BRIEF DESCRIPTION OF THE APPARATUS

A simplified sketch of the apparatus is shown in Fig. 1. A source of P 32 (~50 microcuries) on an area of about $\frac{1}{4}$ square centimeter is mounted on the blown glass film, S (0.4 mg/cm^2). The active deposit faces the electron multiplier. The beta-particles are deflected by the 90° spectrometer and are detected in the Geiger counter which starts a 17-microsecond sweep on a cathode-ray tube. The electron multiplier pulse is clipped by a pulse or line, and is applied as intensity modulation on the cathode-ray tube, making a dot about $\frac{1}{5}$ microsecond in duration. A continuously moving film records the position of the electron multiplier pulses. Every six minutes a row of one microsecond calibration dots automatically appears on the sweep. The recoil ion time of flight distribution is plotted directly from the film record.

An important part of the equipment, not shown in Fig. 1, is a heater (two 0.075-cm diameter tungsten wires each one cm long) located 2 or 3 mm to the left of the source film. This heater serves two important functions. One is to keep the surface continuously warm by radiation from the dull red heater wires. This continuous heating permits the P 32 surface to maintain its original characteristics for 5 to 10 days. The second purpose of the heater is to give the radioactive surface a thermal electron "bath" for a few seconds every twelve hours. These electrons, emitted from the heater while it is run for short times at a high temperature, drift around to the front of the surface and neutralize the positive surface charge built up by the departing beta-particles.

The surface S is a blown Pyrex film freshly coated in the same vacuum system with a just visible gold film. On top of the gold is evaporated a LiF or

[8] J. L. Berggren and R. K. Osborne, Phys. Rev. **74**, 1240 (A) (1948).
[9] Cook, Langer, and Price, Phys. Rev. **74**, 548 (1948).

MgF_2 film. These insulating films have a "work function" which is high enough, at least in spots, to let some of the recoil ions (sulfur, 10.3-ev ionization potential) escape charged. Potentials of 10 to 15 volts still can build up in a period of 3 or 4 days, so that regular "baths" of electrons are necessary to keep surface charges from influencing the recoil ions. The heater cannot be continuously hot enough to emit appreciable numbers of electrons because this causes the electron multiplier to have a very high background. Even before this limit is reached there is some evidence that operating above a dull red temperature causes a deterioration of the surface (possibly diffusion of the P 32 atoms into the substrate) and slow evaporation of the P 32 atoms. The effects of too high heater temperatures are to noticeably increase, in 5 to 10 hours, the relative numbers of low momentum recoil ions, and to cause the electron multiplier background to increase steadily.

With the aid of the heater and a good vacuum (10^{-7} mm of Hg) surfaces show no noticeable changes for 4 to 6 days, but between 10 to 16 days there is some evidence that surface losses on the part of the recoil ions is on the increase. Without a heater, the surfaces badly deteriorate in a few hours. This remarkable and unexpectedly long life of the P 32 surfaces makes possible measurements that would otherwise be very difficult, if not impossible, to perform. When working with coincidence type experiments in which the effects are the order of the background, only efficient geometry and long observation time are of any avail in obtaining precision results.

It is interesting to consider the purity requirements on the radioactive material. To form a 50-microcurie monolayer source of P 32 on a 0.25 cm^2 surface requires that $\sim 1/500$ of the available surface area be occupied by P 32 atoms. This in turn requires that the maximum amount of inert atoms accompanying the P 32 as it is evaporated onto the final surface is about one microgram per millicurie. All of the significant data reported here was obtained from two shipments specially purified carrier free P 32 in weak acid solution obtained from Oak Ridge. One shipment had less than 40 micrograms and the other about 80 micrograms of non-volitile matter per millicurie. This material is twice evaporated in forming the final surface. After the first evaporation the active deposit becomes invisible, giving a separation factor of at least 20:1. After the second evaporation, the performance of the recoil ions is the only test of source thinness.

It should be noted that initially the P 32 atoms are on the average widely separated. They do not evaporate easily except at temperatures above 600°C, but their migration on the surface may still occur. Migration of barium on a tungsten surface is known to occur 250 degrees below the evaporation temperature,[10, 11] and it occurs in mercury at liquid air temperature.[12]

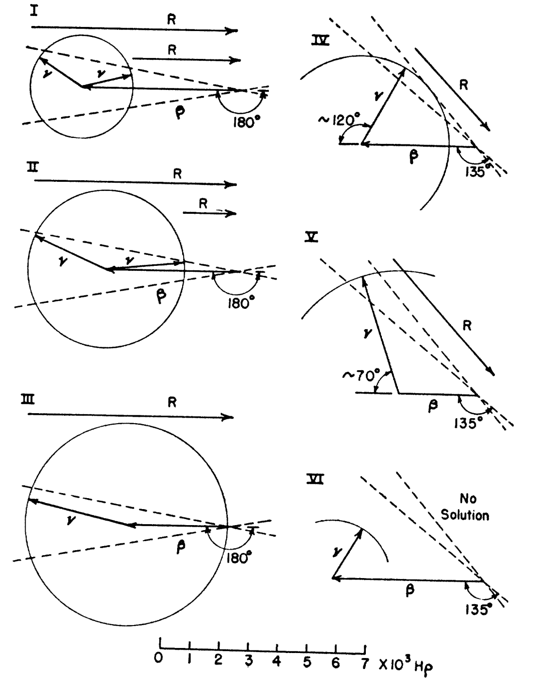

FIG. 2. Some vector diagrams of momenta in the beta-decay of P 32. The diagrams show six different geometrical arrangements of the electron (β), recoil ion (R), and neutrino (ν) momentum vectors that were tested experimentally. The dotted lines show the "cone of sensitivity" set by the slit widths of the detection system, into which the recoil ion must go in order to be detected. The magnitude of the neutrino momentum vector is calculated from the conservation of energy.

The beta-spectrometer in Fig. 1 can be used at the 180° (electron-recoil angle) position as shown, or it can be moved to the 135° window. In the latter position, the spectrometer is rotated through 90° so the electrons are deflected perpendicular to the plane of the paper. Because of the shape of the slits, this reduces by a factor of two, the possible variation in angle between the electron and the recoil ions being detected. There is some scattering of the beta-particles in the exit window (8 mg/cm^2) of the vacuum system and in the air of the spectrograph chamber. The wide exit slit of the spectrometer (2.2 cm) and the width of the source (0.5 cm) already make the resolution of the instrument broad. The scattering has been generously allowed for using the observations of Slawsky and Crane[13] on 0.9-Mev electrons. The measurements reported

[10] J. H. de Boer, *Electron Emission and Absorption Phenomena* (Cambridge University Press, London, 1935), p. 112.
[11] J. A. Becker, Trans. Faraday Soc. **28**, 155 (1932).
[12] I. Estermann, Zeits. Physik. Chemie **106**, 403 (1923).
[13] M. M. Slawsky and H. R. Crane, Phys. Rev. **56**, 1203 (1939).

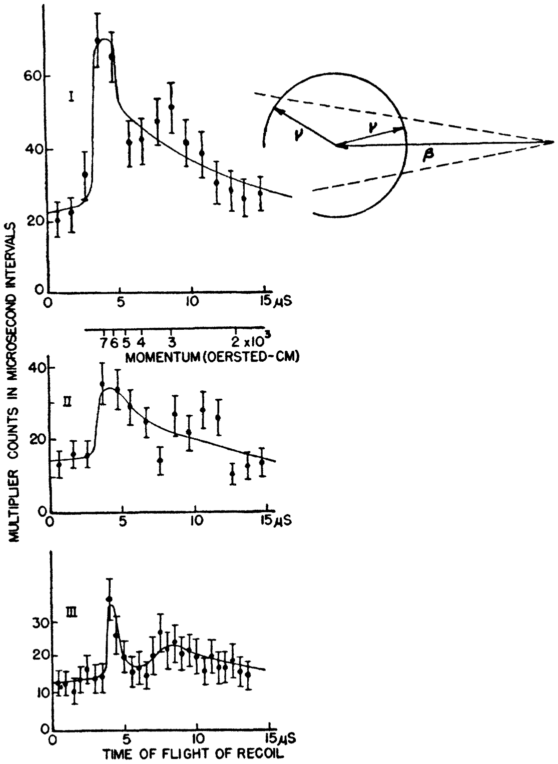

FIG. 3. Time of flight of recoil ions from three "poor" surfaces. There are far too many low momentum recoil ions for the geometry shown. These surfaces are thought to be over-laid with varying amounts of inert material.

here were made with electrons between 0.5 and 1.2 Mev.

The spectrometer is calibrated by measuring the complete beta-spectrum of the actual P 32 sources used in the recoil experiments. The beta-spectrum does not deviate from a straight line on a Fermi plot down to $3600\,H\rho$, and at $2600\,H\rho$ the points fall 10 percent below the line as the effects of scattering and absorption become noticeable.

The electron multiplier aperture subtends a solid angle of 38 square degrees, as viewed from S.

Improved equipment should have a vacuum spectrometer located at 180°, 135°, and 90° each recording data simultaneously from the same electron multiplier.

IV. SOME PREDICTIONS WITH MOMENTUM VECTORS

An hypothesis is tested by making predictions and then testing these predictions experimentally. The hypothesis that the neutrino acts like an ordinary particle or photon and carries away momentum whose magnitude is determined by the missing energy can be tested using the apparatus in Fig. 1. Some predictions, made easily by graphical methods, are shown in Fig. 2. The length of the neutrino momentum vector is fixed by the conservation of energy and is calculated from Eq. (1). Its direction is indeterminate although it may be influenced by some unknown angular correlation with respect to the electron. Dotted lines show the "cone of sensitivity" into which the recoil vector must fall for the recoil ion to be detected. Thus, the slits of the experimental apparatus permit only those neutrinos which have certain specified directions to produce detectable recoil ions. From the intensity of these groups of recoil ions, one can calculate the intensities of the neutrino groups that cause them, thus, measuring the neutrino-electron angular correlation.

For electron energies in excess of 0.5 Mev, the sum of the magnitudes of the neutrino and electron momenta is nearly constant (7000 to 7200 oersted-cm).

In interpreting the vector diagrams of Fig. 2 one must remember that the electron momentum vectors are only the center values of a group whose spread is ± 15 to ± 20 percent in length, and whose spread in direction is ± 5 to ± 10 degrees. An averaging of the effects of these variations must be made, and the time resolution (0.5 microsecond) of the time of flight measurements be taken into account, before exact predictions are possible regarding experimental results.

Consider first the geometry of case I. Here the electron momentum is $\frac{3}{4}$ of the maximum value of 7200 oersted-cm. The neutrino momentum, from Eq. (1), is very nearly $\frac{1}{4}$ of 7200 oersted-cm (or $H\rho$). For "forward" neutrinos, a high momentum ($7200\,H\rho$) recoil is formed. For "backward" neutrinos a low momentum ($\frac{1}{2}\times 7200\,H\rho$) recoil is formed. For neutrinos having an angle of about 90° with respect to the electrons, the recoil should be outside the cone of sensitivity, and not be detected. Thus, for case I of Fig. 2, one should observe two distinct groups of recoil ions. As will be shown later, the high momentum recoils are clearly visible experimentally. A careful search for the lower momentum group of recoils has thus far been unsuccessful. These low momentum recoils are hard to observe for three reasons: (1) the solid angle available to the backward neutrino is only $\frac{1}{4}$ that available to the forward neutrino; (2) the spread (about $\pm 800\,H\rho$) in electron momentum causes the low momentum recoils to be spread over $\pm 1600\,H\rho$ around an average value of $3600\,H\rho$. This same uncertainty in the electron momentum causes, however, a negligible spread in the recoils due to the forward neutrinos since, to a good approximation, the electron's loss is the neutrino's gain and the two vectors add up to the same value of nearly $7200\,H\rho$; (3) the low momentum peak is hard to observe against the random background since, on a time of flight scale, a given momentum interval centered at $3600\,H\rho$ is spread over about four times as many microseconds as is the same momentum interval centered at 7200 $H\rho$. These three effects attentuate and smear out the low momentum peak, making it hard to distinguish above the random background.

Case II is similar to I except that the low momentum peak due to the backward neutrino is even weaker and more diffuse than before. The high momentum peak should still have a value of 7200 $H\rho$, but its intensity per beta-particle should be lower since the solid angle available to the neutrino is less.

Case III has only one possible solution, namely recoils of about 7000 $H\rho$. These recoils should be only $\frac{1}{4}$ as intense per beta-particle as in case I since the solid angle available to the neutrino is only $\frac{1}{4}$ as large. This prediction assumes that the angular correlation function of the electron and neutrino does not change rapidly over the angles involved (0 to 60°). This case is particularly important since it is here possible to detect the presence of low momentum recoils which are spurious, due most probably to scattering and surface losses of the recoils. Since there is only one possible solution of the momentum triangle for a single neutrino, the presence of recoils at low energies can be explained by multiple neutrinos or by a poor surface, the latter explanation being far more likely. A sharp high momentum peak of recoils followed by no low energy recoils is thus considered to be the best test of a true monolayer surface. If there were multiple neutrinos with any randomness in their relative directions, one would not obtain the sharp high momentum peak predicted by cases I, II, and III since, on the average, their momenta would partially cancel each other. This would cause a diffuse group of recoil ions.

Cases I, II, and III of Fig. 2 form a sort of null method of detect for the neutrino. The mere presence of a sharp high momentum group of recoils coincident with lower momentum groups of electrons shows that there is a unique amount of momentum missing in each of the three cases and that the missing momentum increases in direct proportion to the missing energy. A further important prediction is that there should be a progressive change in the intensity per beta particle of the high momentum recoil peak due to the change of the solid angle available to the neutrino.

Case IV has nearly the same electron momentum as case III. One is looking for recoils in a different direction, 135° with respect to the electron instead of 180°. The neutrino, though backward, now has an appreciable available solid angle, and can form low momentum recoil ions in the region of 3000 to 5000 $H\rho$.

Case V differs from the previous one only by having a lower electron momentum. This predicts a higher average recoil momentum because of the new shape of the triangle. Thus, comparing the cases IV and V, the lower momentum electrons are associated with the higher momentum recoils—an effect that is most unlikely except on the neutrino hypothesis. This effect also gives more information about the surface, for if the average recoil groups observed in IV and V actually shift momentum as predicted it is unlikely that they are all due to some spurious effect such as scattering.

Case VI is a triangle that is insoluable by the efforts of the neutrino alone. At best the neutrino can make a group of medium momentum recoils which fail to enter the cone of sensitivity by 20 or 30 degrees. If there is no scattering of the recoils at the surface, one should obtain no recoil ions above the chance background. This test therefore makes possible an estimate of the effects of surface scattering which is potentially the most important sources of error in this type of experiment.

In addition, to the six cases shown in Fig. 2, some measurements were also taken, intermediate to cases IV and V, where the electron-neutrino angle is about 90°.

The rest of the paper consists of a description of

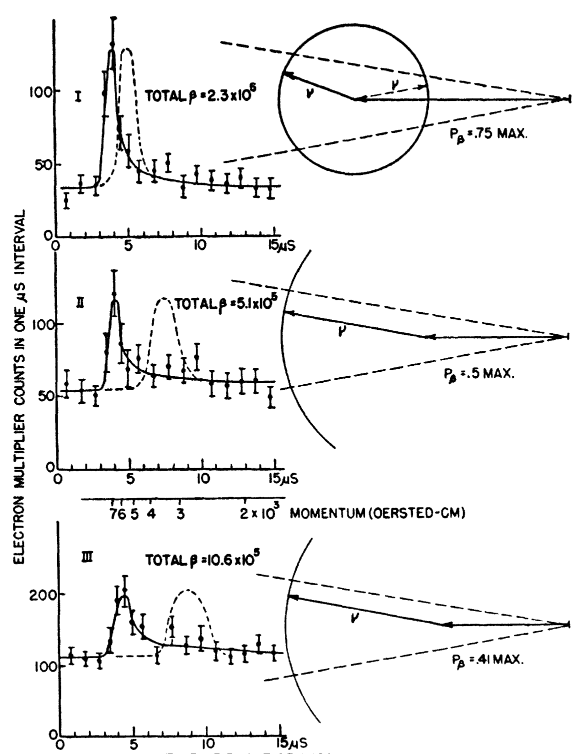

FIG. 4. Time of flight of recoil ions from surface A. The dotted curves (arbitrary amplitude) show what the recoil ion spectra would look like if there were no neutrino. The continued presence of the high momentum peak of recoils as the electron momentum is progressively reduced is evidence for a single neutrino. "Total β" means the total number of electrons detected during the observation of the complete curve.

the experimental observations made under the various conditions shown in Fig. 2. It can be stated, in anticipation, that for some sources the predictions of Fig. 2 are indeed fulfilled, and that scattering effects, though noticeable, are not so large as to obscure the essential agreement between theory and experiment.

V. EXPERIMENTAL RESULTS

Most of the sources have recoil spectra similar to the three shown in Fig. 3. There is evidence of a peak at about 7000 $H\rho$ as predicted by case I of Fig. 2, but there is a strong low momentum (long time of flight) "tail." This tail varies in intensity through a wide range for different sources. It might be explained by multiple neutrinos, but surface scattering due to the thickness of the source is far more likely. As will shortly be described, other surfaces for which the 7000 $H\rho$ peak stands out much better compared to the background show practically no evidence of a low momentum tail. The assumption is made that it is a spurious effect caused by the surface.

The tendency to form a second peak in the neighborhood of 8 or 10 microseconds also appears to be a spurious effect and not due, as was first supposed, to a strongly backward neutrino. When carefully studied, this second peak proves to be erratic and never to be really distinct above the background. When the highest purity radioactive material is used, this second peak simply vanishes.

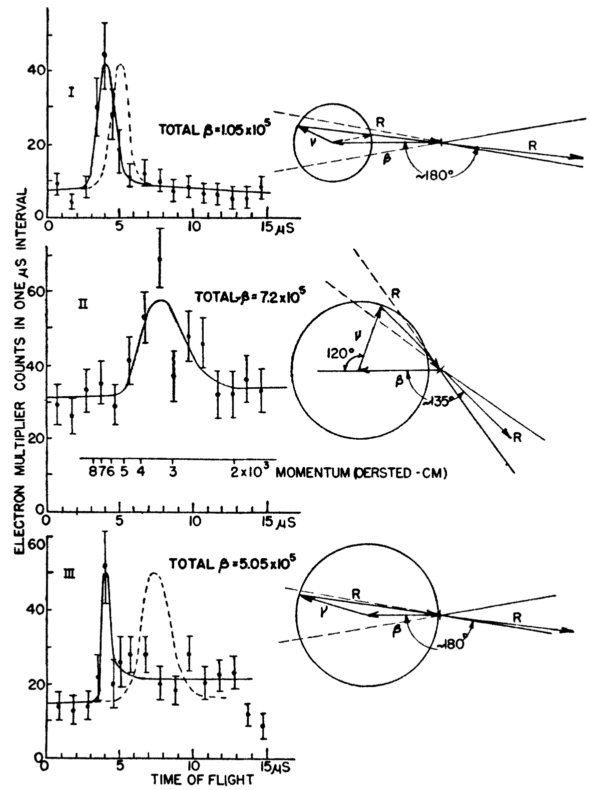

FIG. 6. Time of flight of recoil ions from surface B. An interesting point about these data is the difference between curves II and III. The only difference in the apparatus for these two cases is that the beta-spectrometer is moved from the 180° window to the 135° window (see Fig. 1). The dotted curves show what the recoil spectra would look like if the recoils received momentum only from the electrons.

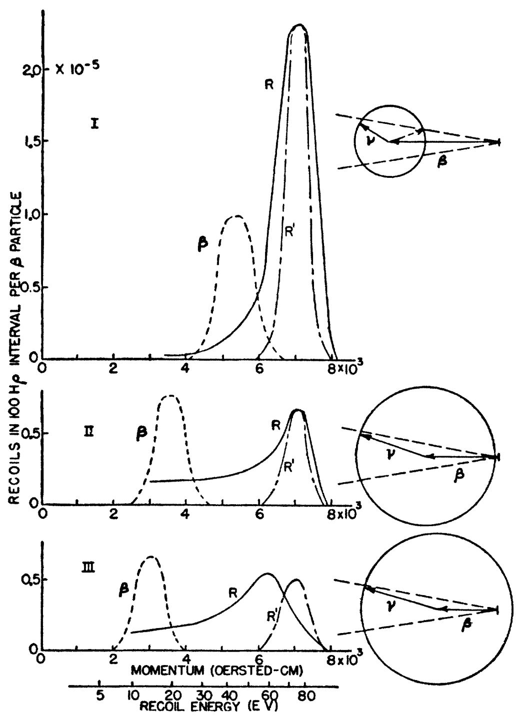

FIG. 5. Momentum spectra of the recoil ions in Fig. 4. β = the electron spectrum (arbitrary amplitude), R = the observed recoil momentum spectra (less background), R' = the calculated recoil momentum spectrum, normalized in amplitude to the observed spectrum, assuming a single neutrino, and taking into account the finite resolving power of the apparatus. The observed decrease in intensity of the high momentum recoil peak is predicted by the decrease in the solid angle available to the neutrino inside the cone of sensitivity.

Figure 4 shows recoil ion time of flight spectra for a typical "good" surface. Figure 5 shows the momentum spectra for the same data, background subtracted, along with the recoil spectra predicted by the neutrino. Several conclusions can be drawn from these data.

(a) The clear cut distinction between the observed recoil momentum and the electron momentum argues for a single neutrino for which the energy momentum is c (±20 percent, estimated error). The fairly sharp recoil group shows that the recoil ions escape without too much interference from the source, in any case, the improvement over the data in Fig. 3 is very marked.

(b) The progressive decrease in the absolute intensity, Fig. 5, of the 7000 $H\rho$ peak as the solid angle available to the neutrino decreases, is predicted by a neutrino whose angular correlation with respect to the electron does not change rapidly between 0° and 60°. For example, in curves I and II of Fig. 5, the neutrino vector changes length by a factor of two making the available solid angle change by a factor of four, and the observed intensity of the peaks changes by 4.

(c) There is no evidence above background of a second low momentum (4500 to 2500 $H\rho$) peak due to the backward neutrinos. This peak would be about twice background if there were a backward $(1-v/c\cos\theta)$ neutrino-electron angular correlation. On some surfaces a small low momentum "tail" appears, following the 7000 $H\rho$ peak, for the geometry of curve I, Fig. 4. One might think this to be due to backward neutrinos, but an examination of the data obtained with the geometry of curve II, Fig. 4 also shows a similar low momentum tail. For this second case, the neutrino cannot possibly produce a low momentum peak. One concludes that the tail is due to scattering of that fraction of the recoil ions that are overlaid or otherwise obstructed by inert atoms.

A second "good" surface of P 32 on a LiF substrate is shown in Figs. 6 and 7. The top and bottom graphs support the same conclusions as just discussed above. In addition, the distinctly different recoil spectrum for the center case (electron-recoil angle 135°, electron momentum slightly over ½ maximum) gives some additional information.

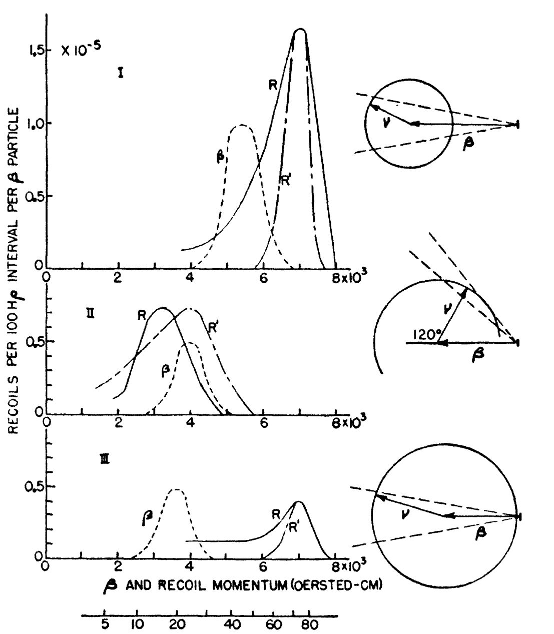

FIG. 7. Momentum spectra of the recoil ions in Fig. 6. β=electron spectrum (arbitrary amplitude). R=observed recoil momentum spectrum, less background. R'=calculated recoil momentum spectrum, normalized in amplitude to the observed spectrum, and taking into account the finite resolving power of the apparatus.

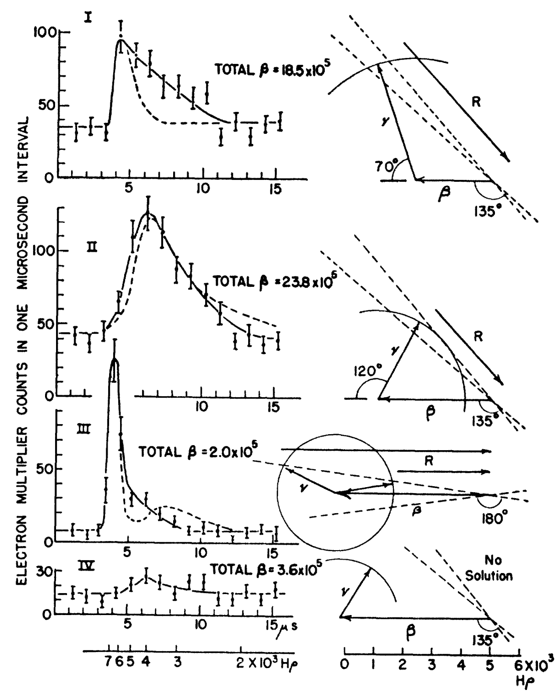

FIG. 8. Time of flight of recoil ions from surface C. The dotted lines show the calculated shape (arbitrary amplitude) of the recoil time of flight spectra taking into account the resolving power of the apparatus. The small low momentum peak in curve III was calculated assuming a random neutrino. This peak would be about 7 times larger for a backward $(1-v/c\cos\theta)$ neutrino, and about five times smaller for a forward $(1+v/c\cos\theta)$ neutrino. Curve IV shows that there are some spurious low momentum recoils that are not caused by neutrinos alone.

(a) Note that the essential difference between the geometry of curves II and III of Fig. 6 is the direction of the recoils with respect to the electrons. Since the recoils are always examined approximately perpendicular to the surface, the two figures differ only in the location of the beta spectrometer (see Fig. 1). We conclude that the high momentum recoil groups are not noticeably scattered through 45°. Otherwise, the spectra would not be so distinctly different. There is a low momentum "tail" on curve III which must be spurious, and whose total intensity is about 7×10^{-5} recoils per beta-particle. On the other hand, the recoil group in curve II has a total intensity of 16×10^{-5} recoils per beta-particle. If the spurious low momentum recoils present in III are also scattered through angles up to 45 degrees with any appreciable intensity, we estimate that up to $\frac{7}{16}$ of the recoils in curve II may be spurious. This method of making a correction for scattering is not very precise. It does, however, give the approximate magnitude of the correction, and more important, the direction of the correction. Furthermore, as will be pointed out when discussing observations with the insolu-

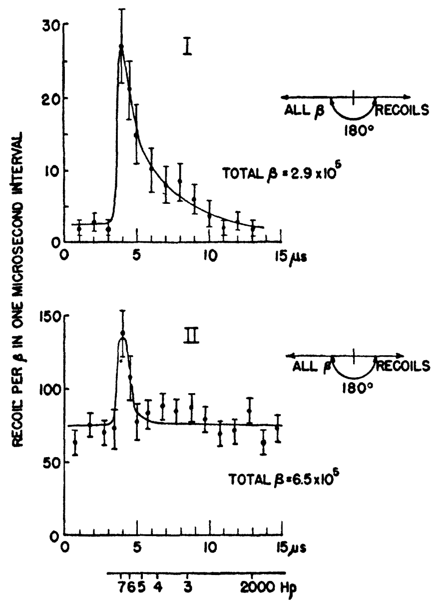

FIG. 9. Recoil ions from the complete electron momentum spectrum. The upper curve is from earlier published data by the author and its shape agrees rather well with that predicted by backward $(1-v/c\cos\theta)$ neutrino-electron angular correlation function. The lower curve is taken from the same surface as Fig. 4, and agrees only with a forward, or at most a random neutrino. The difference in the relative magnitude of the backgrounds is due to the much higher intensity of the source for II. The low momentum "tail" on curve I is apparently due to surface losses and scattering of the recoil ions which, without a beta-spectrometer, is hard to distinguish from a backward neutrino.

able triangle of case VI, Fig. 2, a different geometry suggests approximately the same correction.

(b) The presence of what appear to be genuine recoils at 3 to 4 thousand $H\rho$ on curve II suggests that recoils of this low energy really escape from the surface and can be detected. This removes one possible explanation of why the second low momentum peak in curve I is not observed, namely that some unknown surface effect prevents the recoil ions of initially low energy from escaping at all, or if they do escape, makes them neutral and thus undetectable.

(c) The predictions of the neutrino hypothesis agree rather well with all three observed recoil spectra as can be seen from Fig. 7.

Further information can be obtained by studying the observations on a third "good" surface. These data are plotted in Fig. 8. This source was several times weaker than the two others already discussed, and required longer observation time, the curves I through IV requiring 40, 47, $8\frac{1}{2}$, and 21 hours, respectively. These observations were not made in the simple sequence suggested by the drawing, but are compiled from 16 different films with each successive film having a different geometry. This same procedure was also followed on the other surfaces described here.

We shall now discuss the significance of the data in Fig. 8, starting with curve III since it tests the monolayer character of the source.

(a) At first sight, curve III shows more of a low momentum tail than the same geometry in the earlier surfaces, and one might suspect it of being inferior. However, the random background is considerably lower, and it may be that the imperfection is no worse than for the earlier surfaces, but merely more easily noticed. Furthermore, this tail is not due to a backward neutrino since it also appears for the geometry of case III, Fig. 2 where the neutrino can not be the cause. The dotted curve in III, Fig. 8, shows the low intensity low momentum peak which would be caused by a random neutrino. A more forward neutrino, which is implied by the other observations, would make this peak still smaller and more obscure. Failure to observe it is not surprising. In any case, a strongly backward neutrino is rejected.

(b) A comparison of curves I and II of Fig. 8 shows that there is a distinct difference in the average momentum of the observed recoil groups. One group has a maximum at about 5 to 6 thousand $H\rho$, and the other at 3 to 4 thousand $H\rho$. This effect is predicted by the neutrino hypothesis as can be seen from the vector drawings and the dotted curves. Here is direct experimental evidence that the higher momentum recoils are associated with the lower energy electrons, as the neutrino hypothesis requires. The presence of a low momentum "tail" on curve I in contrast to the predictions indicates that there are some surface losses. How many of the recoils in the tail are initially due to the 70-degree neutrino group under study, and how many are due to entirely irrelevant neutrinos followed by surface scattering, is not certain. The dotted curves are arbitrarily normalized to the peak values of the solid experimental curves merely to show relative shapes. It is probable that over half the recoils in I are really due to the 70° neutrino group. The same characteristic shift in the neutrino momentum, visible in curves I and II of Fig. 8, is also observed on other surfaces, but with poorer statistical accuracy.

(c) We now consider the implications of the data of curve IV where there are supposed to be no recoils which can enter the cone of sensitivity. Actually, there is evidence of a peak of recoils in the 3 to 4 thousand $H\rho$ region. This peak must be due to scattering through 20 or more degrees of those recoils which are formed by the electron and neutrino vectors selected by the particular geometry. The total intensity of this spurious peak is $\sim 6\times 10^{-5}$ recoils per beta-particle. One can obtain an independent estimate of the intensity of the spurious low momentum recoil ions from a different geometry, the data for which is not shown in Fig. 8.

This geometry is the same as that of case III, Fig. 2, which, for the surface of Fig. 8, shows low momentum spurious recoils of intensity 5×10^{-5} recoils per beta-particle. Thus, the spurious recoil intensity is about the same at both 180° and 135° with respect to the beta-particles. This suggests that there is a diffuse group of low energy recoils of approximately constant intensity spread over a wide angle with respect to the electrons. One infers that these recoils are so badly scattered that they have lost most of their original correlation with the electron and neutrino, and form a sort of background against which the true events must be distinguished. For the surfaces in Figs. 6 and 8 this background, presumably due to scattering, has about the same intensity, and makes necessary a minus 45 percent correction to the observed intensity of the recoil groups in case II of each figure.

One of the big advantages of using a beta-spectrometer for neutrino recoil studies is now apparent. It is possible to make quantitative estimates of the effects of scattering of the recoils by the surface. Scattering is probably the most serious source of error in this type of measurement, and is very difficult if not impossible to detect if the whole beta-spectrum is used. In fact, the previous results of the author[3] using the entire electron spectrum, in which the data favored a backward neutrino, were obtained from what is now recognized as a "thick" or at least partially overlaid source. This is demonstrated graphically in Fig. 9 where the recoil spectrum at $\sim$180° with respect to the whole electron spectrum is plotted. Curve I is from Fig. 3 of the earlier paper on P 32, and curve II is for the same surface as shown in Fig. 4 of this paper. The difference in the intensity of the random background is due to the fact that the source used in II is much more intense than that used in I. For the more recent source, II, the smaller number of low momentum recoils is apparent. Whereas the earlier curve, I, agrees rather well with the $(1-v/c\cos\theta)$ neutrino, curve II agrees well with any angular correlation that is random or more forward than random. Thus, the unexplained abundance of low momentum recoils in this early data, which made the conclusions about the neutrino-electron angular correlation tentative, is now definitely assignable to surface scattering and losses.

We now consider the question about the recoil ions of different velocities escaping in the charged state. Since, as will shortly be shown, only about 3 to 6 percent of the recoil ions from a LiF substrate, and $1\frac{1}{2}$ to 3 percent from a MgF_2 substrate, escape charged, the problem naturally arises whether the fraction that escapes charged depends on the recoil velocity. The angular correlation between electron and neutrino is determined from the measured intensity of recoil ion groups whose average velocity ranges from 4×10^6 cm/sec. for 7000 $H\rho$ to 2×10^6 cm/sec. for 3500 $H\rho$. If the chance of escaping charged is appreciably velocity dependent, then the observed recoil intensities, even after scattering corrections are made, are still in error.

Unlike the scattering corrections described above, there seems to be no presently feasible way to make an experimental correction for the effect of the ion velocity upon its chance of escaping charged. Fortunately, a simple theoretical argument gives a definite answer to the neutralization problem, whereas theoretical analysis of surface scattering is hopelessly complicated.

The theoretical argument hinges on the fact that the departure of the recoil atom from the surface is, from the viewpoint of the electronic states, an adiabatic process. If the separation of the atom from the surface were infinitely slow, the electron density near the substrate and near the recoil atom depends only on the form of the Hamiltonian, and not on its rate of change. The electronic state existing during this adiabatic process will be called the initial state, m. If, however, the recoil atom moves with appreciable speed, the changing Hamiltonian can excite an electronic state, k, in which the relative electron density near the substrate and near the recoil atom may be different than for state m. The criterion for the validity of the adiabatic approximation is that the change in H during the Bohr period for the transition $m\rightarrow k$ is small in comparison with the energy difference between these two states. The magnitude $|a_k|$ of the probability amplitude for state k is given by,[14]

$$|a_k|\sim\left|\frac{(1/\omega_{km})(\partial H/\partial t)}{E_k-E_m}\right|, \tag{2}$$

where $\omega_{km}=(E_k-E_m)/\hbar$. We now assume that H changes most rapidly during the time Δt that the atom, of velocity v, moves the first angstrom unit of its path as it departs from the substrate. We also assume that the change ΔH is the order of 5 ev, and that $E_k-E_m\simeq5$ ev. These energy values cannot be too far off since the first ionization potential of the sulfur recoil atom is 10.3 ev, and the upper limit of the recoil spectrum shows that the loss in energy of the recoil ion is less than 8 ev. For a recoil atom moving with a velocity of 4×10^6 cm/sec., $|a_k|\sim1/20$, and a_k^2, the probability of the system being in the excited state k, is 1/400. For the slower recoil atoms moving at 2×10^6 cm/sec., a_k^2 is 1/1600. Therefore, the chance that the motion of the recoil ion will excite a state different than the ground state is seen to be small, and the adiabatic approximation is justified. Only at considerably higher velocities would the value of

[14] L. I. Schiff, *Quantum Mechanics* (McGraw Hill Book Company, Inc., New York, 1949), p. 210.

$\partial H/\partial t$ be large enough to excite higher electronic states and thus affect the relative density of electrons at the substrate and at the recoil atom.

The recoil ions are all singly charged. This is known by measuring their velocity after being artificially accelerated with energies large compared to their initial energy. A sharp row of dots appears on the film at an e/m value of singly charged, mass 32.

Although all of the data discussed thus far are from P 32 surfaces on a LiF substrate, one good surface was formed on a MgF_2 substrate. The shapes of the recoil spectra from this source are in excellent agreement with the corresponding spectra from sources on a LiF substrate. Only in one respect is there any significant difference, and that is in the intensity of the recoil groups per beta-particle. The recoil groups from MgF_2 are only about $\frac{1}{2}$ as intense as are the corresponding groups from a LiF substrate.

According to L. G. Shultz,[15] in a layer which averages about 20 angstroms in thickness, MgF_2 shows by x-ray analysis, no structure, while the LiF of the same average thickness shows structure of the order of 50 angstroms. Blown glass films like those used as the foundation surfaces of these experiments have remarkably small vertical irregularities, of the order of 5 angstrom units in height, according to R. C. Williams.[16] Thus, it is probable that the MgF_2 substrate is smoother than the LiF on a 5 to 50 angstrom scale. That there is any improvement on the atomic (1–2 angstroms) scale is not likely.

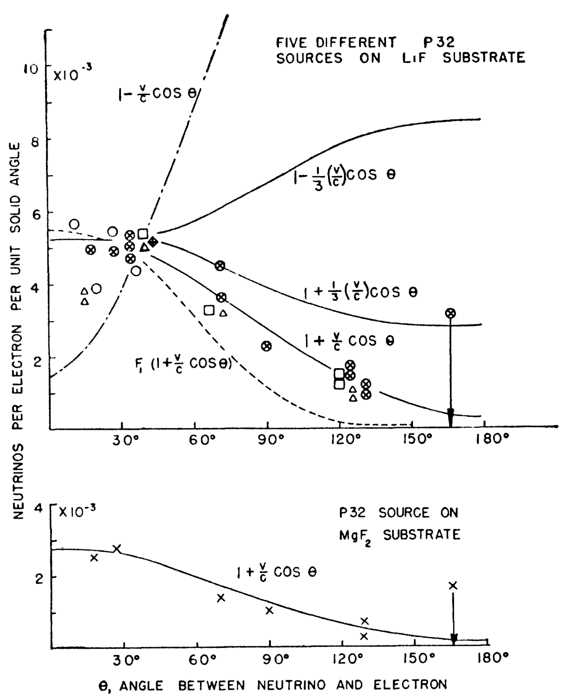

FIG. 10. Experimental neutrino-electron angular correlation. The point at 165° with the downward pointing arrow means that the correlation function cannot lie above the value indicated, although it can lie anywhere below. Each point is the average probability over an interval in neutrino-electron angle ranging from $\pm 15°$ to $\pm 35°$. $F_1(1+v/c\cos\theta)$ is the theoretical correlation for a first forbidden transition if the neutrino-electron interaction by itself would predict a correlation of $(1+v/c\cos\theta)$. Surface A (Fig. 4) = ○, Surface B (Fig. 6) = △, Surface C (Fig. 8) = ⊗.

The effects of scattering on the MgF_2 substrate can be described by the following numbers. The total intensity of the recoil group for the geometry of case IV, Fig. 2 is 7.2×10^{-5} recoils/beta-particle, or about half as intense as for the LiF case. The total intensity of spurious low momentum recoils measured with geometry III of Fig. 2 is 3.6×10^{-5}, again about half as intense as for LiF. No recoils are visible above the random background for geometry VI of Fig. 2, but if there were as many as $\sim3\times10^{-5}$ spurious recoils per beta-particle, a peak would have been visible. Thus, this second case sets an upper limit on the intensity of the spurious low momentum recoil ions which are scattered through $\sim30°$ at $\sim3\times10^{-5}$. The conclusion is that the scattering for a MgF_2 substrate is no worse, and possibly better than for LiF substrate.

The intensity of these low momentum, spurious recoils makes possible an estimate of the fraction of the P 32 atoms that are scattered. To make this estimate, we must make an assumption about the violence of the scattering. A fairly pessimistic estimate is that the scattering, when it occurs at all, removes practically all of the original angular correlation that the recoil had with the electron and the neutrino. For example, suppose that these recoils are scattered uniformily through 2π steradians. We further assume that the neutrino-electron angular correlation is $(1+v/c\cos\theta)$ which, as will shortly be demonstrated, agrees best with the observations. Now, to account for the observed intensities of (a) the unscattered recoils (i.e., the sharp high momentum recoil groups at electron-recoil angles of 180°), and (b) the diffuse, scattered recoils ($\sim6\times10^{-5}$ recoils in 38 square degrees/beta-particle, LiF substrate), a simple calculation shows that it is necessary that two things be simultaneously true: (1) 6 percent of all the recoils escape charged, and (2) 50 percent of the recoils are scattered and 50 percent are unscattered.

If, alternatively, we assume that the scattered recoils are spread over only one steradian, which is the region over which they have been observed, we then must conclude: (1) $3\frac{1}{2}$ percent escape charged, and (2) 15 percent are scattered and 85 percent are not scattered. Since one actually observes scattering through a solid angle of one

[15] L. G. Shultz, private communication.

[16] Robley C. Williams, J. App. Phys. 20, 98 (1949).

TABLE I. Inferences about the form of the neutrino-electron interaction, based on the data of Fig. 10.

Type of transition	Form of neutrino-electron interaction: Most probable	Possible	Rejected
allowed	polar vector $(1+v/c\cos\theta)$	tensor $(1+\frac{1}{3}v/c\cos\theta)$	scalar and pseudo scalar $(1-v/c\cos\theta)$ axial vector $(1-\frac{1}{3}v/c\cos\theta)$
first forbidden	tensor $(1+\frac{1}{3}v/c\cos\theta)$ axial vector $(1-\frac{1}{3}v/c\cos\theta)$	polar vector $(1+v/c\cos\theta)$	scalar and pseudo scalar $(1-v/c\cos\theta)$

steradian, the figure of 15 percent scattered recoils is a minimum.

Similarly, for the MgF_2 substrate, $1\frac{3}{4}$ to 3 percent of the recoils escape charged, and 15 to 50 percent are scattered.

Presumably the P 32 atoms from which these scattered recoils come are hidden in cracks or behind surface obstructions so they have no direct path of escape toward the electron multiplier. If they were completely overlaid by inert material they probably would not escape at all. Since surfaces will usually be "rough" on an atomic scale there may be little hope of ever making a surface that is completely free from scattering, and therefore even "good" surfaces will have 15 to 50 percent of the escaping recoil ions badly scattered.

One might suppose that this amount of scattering would completely obscure the influence of the neutrino. Actually it is not as bad as it seems, since the extra randomness, in direction and time of flight, caused by the scattering makes these recoils to appear very much like the ordinary random background, making it higher than usual in the region of 5 to 15 microseconds. This extra background is identified, and corrected for, by studying recoil spectra for those cases where the neutrino by itself cannot cause true coincidences.

VI. THE EXPERIMENTAL DETERMINATION OF THE NEUTRINO-ELECTRON ANGULAR CORRELATION FUNCTION

The data from six different P 32 sources, all qualifying as "good" and corrected for scattering by the experimental method described in the previous section, are used to calculate the neutrino density per unit solid angle at various directions with respect to the electron. Figure 10 shows the experiment's points and also various angular correlation functions predicted by the different formulations of the Fermi theory.[7] v is the velocity of the electron. The function $F_1\cdot(1+v/c\cos\theta)$ is for a first forbidden transition when $(1+v/c\cos\theta)$ is the angular correlation for an allowed transition. Hamilton[7] shows that F_1 has the form, $(p/2q+q/2p+\cos\theta)$ where p is the electron momentum and q is the neutrino momentum. In the center region of the electron spectrum where $p\approx q$, F_1 has the approximate form $(1+\cos\theta)$. For the accuracy of observations made here, this approximation is good enough. For the most extreme case, $p=3q$ for the points at $\theta=35°$. Thus, $F_1(1+v/c\cos\theta)$ is very nearly $(1+\cos\theta)^2$.

The points at 165° with the vertical arrow beneath them are merely upper limits to the angular correlation function set by the failure to observe recoils from the backward neutrinos for the geometry of I, Fig. 2. If the angular correlation function is really as small near 180° as the other points imply, it is clear that recoils from the backward neutrinos are hopelessly obscured by the background.

The points in Fig. 10 represent an average over an appreciable neutrino electron angle. Those points at values of θ less than 50° are averages for all neutrinos from 0 to 2θ. These points are all taken with the beta-spectrometer at the 180° window (geometry of I–III, Fig. 2). The points at 70°, 90° and 120° are averages of neutrinos with angular spreads of ±15, ±20, and ±35 degrees, respectively.

An encouraging feature about the data in Fig. 10 is the smooth joining of the points with $\theta<50°$ to those with $\theta>50°$. This is significant since the first group of points is taken with an electron-recoil angle of ~180°, and the second group with an electron-recoil angle of ~135°. This involves a physical shift of the beta-spectrometer from the 180° window to the 135° window (Fig. 1), and also its rotation through 90°, making the electron deflection perpendicular to the plane of the figure.

The experimental points at 70°, 90°, and 120° in Fig. 10 have been reduced, before plotting, by empirically determined scattering corrections of 20 percent, 35 percent, and 45 percent.

Even after the above corrections are made, one is not quite sure that the ordinates of the points in Fig. 10 due to high momentum recoils ($\theta<50°$), and those due to the low momentum recoils ($\theta>90°$) have the correct relative values. The reason for this uncertainty lies in the fact that the lower energy recoils (15 to 25 ev) are more easily deflected by surface binding forces than are the high energy recoils (~75 ev). However, the LiF and MgF_2 substrates, which have rather different surface condition as shown by the different fractions of recoils escaping charged, both give the same relative intensities of high and low momentum recoils. This suggests, but does not conclusively prove, that the deflections due to surface binding forces are unimportant.

The result of these considerations is that the only estimate of error of the points in Fig. 10 is the fallible one given by the self-consistency of the different surfaces.

VII. CONCLUSIONS

The observation of distinct groups of recoil ions coincident with electron groups of much lower momentum seems explainable only on the hypothesis that a neutrino takes away the missing momentum in one package. Separate measurement of the missing energy shows it to have the correct magnitude required by the neutrino momentum. One cannot prove, without actually detecting the neutrino later, that it actually carries off the missing energy in the same direction as the missing momentum, but one is hard put to imagine a more likely place for the energy to be located.

Even without applying corrections for surface scattering of the recoils, a backward neutrino is convincingly rejected.

A summary of inferences about the form of the neutrino-electron interaction, based on the data of Fig. 10, is shown in Table I.

If the P 32 transition is second forbidden, the extreme forwardness of the neutrino with respect to the electron required by the angular momentum change, makes it unlikely that observations of the accuracy reported here could distinguish the original correlation due to the basic neutrino-electron interaction.

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Polarization Effects of Vector-Mesons

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Adopting a vector-meson model for the π-meson we study (I) the polarization of π-mesons produced in nucleon-nucleon-collisions; (II) the angular distribution of μ-mesons resulting from π-μ-disintegrations, as depending on the polarization of the π-mesons; (III) the effect of electromagnetic fields on this polarization, in particular; (IV) the depolarization caused by the electric fields in matter. The theoretical results are encouraging for an experimental investigation.

INTRODUCTION

In a previous paper[1] it was pointed out that if π-mesons have spin 1 it is very likely that polarized π-meson beams can be produced, and that various observable effects might result from this polarization. In order to substantiate these expectations, we want to present some theoretical estimates of certain polarization effects for vector-mesons. The choice of the vector-meson model may be justified by recalling that the π-mesons show a strong resemblance to the Yukawa mesons of the field theory of nuclear forces, indicating integer spin. In particular the fact that negative π-mesons captured by nuclei frequently produce large stars favors the assumption that the interaction of these mesons with nucleons is of the Yukawa type.[2] On the other hand, there is hardly any evidence so far to distinguish between spin 0 and spin 1. To decide this question, the most direct approach would be to prove or to disprove experimentally the existence of polarization effects.

[1] G. Wentzel, Helv. Phys. Acta **22** (1949), in press.
[2] J. A. Wheeler and J. Tiomno, Phys. Rev. **75**, 1306 (1949).

I. MESON PRODUCTION

First we want to study the polarization of vector-mesons produced by nucleon-nucleon-collisions. Let nucleons of momentum $\mathbf{p}_0$ impinge on a target; the nucleons embedded in the target shall be described in terms of a given (nuclear) potential field, which seems a reasonable approximation. The initial state of the system is represented by a superposition of plane waves (Dirac eigenfunctions of free spin $\frac{1}{2}$ particles, normalized):

$$\phi_{p_0\lambda_0}(\mathbf{r},\sigma)=u_{p_0\lambda_0}(\mathbf{r},\sigma)+\sum_{p'\lambda'}u_{p'\lambda'}(\mathbf{r},\sigma)(p'\lambda'|R|p_0\lambda_0).$$

R, or rather $S=1+R$, is the scattering matrix corresponding to the target potential assumed. The suffix λ may be used to distinguish the charge states (proton, neutron) as well as the spin states of the nucleon. The transition to be studied, involving