Experiments on the Emission of Neutrinos from P^{32}

CHALMERS W. SHERWIN
Department of Physics, University of Illinois, Urbana, Illinois*
(Received December 18, 1950)

These experiments study energy and momentum conservation in beta-decay. The apparatus, improved over earlier experiments, permits increased accuracy in the measurement of the neutrino-electron angular correlation. It is concluded that the correlation is approximately $(1+\cos\theta)$. Determination of the nature of the dominant interaction in the beta-decay of P^{32} awaits measurement of the nuclear spin. If the spin is one, the tensor interaction is uniquely selected. If the spin is zero, the axial vector dominates. Spin 2 or higher is ruled out by the shape of the beta-spectrum.

It is also demonstrated that in beta-decay the missing energy and the missing momentum obey the relation $p=E/c$ to an accuracy of better than 10 percent.

I. INTRODUCTION

THE neutrino is unique among all the particles studied in physics in that its existence is inferred entirely from the emission process. All other particles can be observed both in emission and absorption. The effect of the neutrino on the parent nucleon and the accompanying electron is the only presently available process by which one can discover anything about the characteristics of this remarkable particle. Since we have only one avenue of approach to the neutrino, it deserves exhaustive exploration. This paper is the third in a series[1] describing experiments of neutrino emission from P^{32}. Each paper in this series is the result of a repetition of the same basic experiment with improved apparatus. The hope is that the experimental errors can be reduced, and so more reliable information about the neutrino can be obtained.

These experiments consist essentially in a measurement of the energy and momentum of the recoil nucleus and of the electron. One then uses only the basic principles of conservation of energy and momentum to infer the momentum and energy of the neutrino. Theoretical predictions regarding the outcome of possible experiments are made with a pair of dividers and a ruler in a simple manner. Appeal to only the most elementary and fundamental physical concepts always makes the interpretation of experiments more convincing.

In these experiments, a surface layer of P^{32} is evaporated in a vacuum on a thin supporting film. The electrons can escape through the film with little scattering, but the recoil ions can be scattered violently as they escape the surface. Even one collision with some surface molecule can either stop the recoil ion (maximum energy about 78 ev) completely, or scatter it so badly that it loses all memory of its original momentum. The most important experimental problem is to distinguish between those recoil ions which have been scattered and those which escape the surface with no substantial change in their original momenta. If one can identify clearly those recoil ions which are not scattered, he can then reach definite conclusions concerning the relation of energy and momentum of the neutrino and also concerning the angular correlation that the neutrino has with the electron.

An effort has been made to work with the lowest possible electron energy, and therefore with a neutrino having the highest possible energy. The neutrino thus produces the greatest possible effect on the recoil ion. A further advantage of this situation is that one can work exclusively with high energy recoil ions, since the recoil momentum is kept quite near its maximum value over quite a range of electron-neutrino angles. When inferring the electron-neutrino angular correlation, one must compare the relative intensities of groups of recoil ions. If these groups all have nearly the same momentum, one has some confidence that their relative intensities are due to neutrino characteristics and not to surface effects.

Electrons going in several different directions are studied simultaneously. This reduces errors due to progressive changes at the surface (e.g., slow adsorption of gas molecules) and also speeds the collection of data. Since it requires three or four days of continuous observation to get even barely adequate statistics for one particular setting of the apparatus, and since even the best surfaces often show deterioration after this length of time, it is important to collect the maximum amount of information in the first few days.

The equipment is completely automatic, and all the data are recorded photographically.

II. THE EXPERIMENTAL EQUIPMENT

Figures 1 and 2 show the apparatus in which the measurements are made. A glass film (300 to 500 μg/cm^2) is successively coated with aluminum (barely visible), lithium fluoride (100 to 1000 atomic layers), and finally with P^{32} (preferably less than one atomic layer). This is all done by evaporation in the upper chamber, Fig. 1. The radiant heater wires are mounted 2 or 3 mm behind the film. They are kept at a red heat except during the evaporation processes. A rough estimate of the temperature of the film when this heater is operating is about 100°C. However, it is effective in

* This work was supported by the joint program of the ONR and AEC.

[1] C. W. Sherwin, Phys. Rev. 73, 216 (1948); 75, 1799 (1949).

preventing what is probably van der Waals adsorption for days at a time.[2] The pressure is 2 to 6×10^{-7} mm of Hg.

The LiF substrate is necessary to provide a high work function surface which will not neutralize the escaping S^{32} ions. If the P^{32} is deposited directly on the aluminum, no recoil ions are observed. If the aluminum film is omitted, electrostatic surface charge effects completely distort the recoil ion momentum spectrum.

After preparation, the radiant heater is turned back on, the source is lowered to the common focal point of the four beta-spectrometers (Fig. 2), and the observations are begun. The magnetic field over the path of the recoils was measured and found to be of negligible importance.

The scintillation counters use anthracene crystals. They detect the magnetically selected electrons and start the sweep on a cathode-ray tube. The pulse, owing to the arrival of a positive ion at the Allen-type electron multiplier, appears as an intensified spot $\frac{1}{5}$ μsec in duration on the cathode-ray tube. This measures the time of flight of the recoil ion. The distance is known exactly, so the velocity is then determined. Each of the recoil ion pulses appearing on the cathode-ray tube is followed by code pulses. These code pulses identify that scintillation counter which initiated the sweep on which the recoil ion pulse appears. The same cathode-ray tube and the same moving film camera record the complete time of flight data of the recoil ions associated with the four different electron directions. In practice, the electrons at the 110° position (Fig. 2) never give any useful information, so that only the three remaining spectrometers were used.

The spectrometers are all operated at the same magnet current, and all select the same momentum interval. Calibration with the 625-kev line of Cs^{137} gives a momentum resolution in which the full width at half-maximum is 15 percent. This spread is mainly due to the fact that the exit slits of the spectrometers are 2 cm wide.

The entire vacuum system is heated to about 100°C to speed outgassing. This process usually continues for several days. Only after the vacuum system is returned to room temperature is a surface formed. Helium is used to fill the system whenever it is brought up to atmospheric pressure.

The P^{32} is purified in an auxiliary system by vacuum evaporation, during which process it is deposited on one of the evaporation filaments eventually used in Fig. 1. Thus, the final surface is formed after two evaporations, each of which has been carefully studied to provide maximum separation from impurities.

[2] H. Frauenfelder has shown (private communication) that the rate of Cd^{102} recoil emission from a surface is greatly increased by raising its temperature one to two hundred degrees C. See also P. B. Smith and J. S. Allen, Phys. Rev. **81**, 381 (1951).

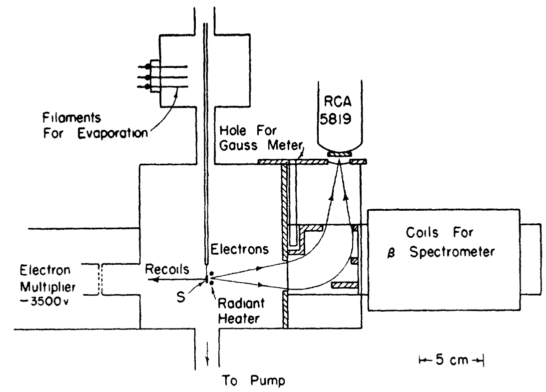

FIG. 1. Apparatus for measuring the momentum of the electrons and recoil ions in beta-decay. The radioactive atoms are on the surface S facing the electron multiplier. The electrons go through S, are deflected in 90° spectrometers, and leave the vacuum through a thin window at the focal point. The velocity of the recoil ion is measured by observing its time of flight from S to the first dynode of the electron multiplier.

III. SOME RESULTS WITH POOR SOURCES

Most of the sources of P^{32} gave no useful information about the neutrino. Apparently all recoil ions that escape these surfaces are badly scattered. Such a surface gives results like those shown in Fig. 3. Here, broad peaks of recoil ions appear above the chance background. This background is determined by those events occurring before true coincidences are possible (0 to $3\frac{1}{2}$ μsec from the start of the sweep). In Fig. 3, the recoil ion momentum distribution is quite insensitive to the direction of the electrons. This is just what is to be expected if violent scattering occurs, and we conclude that this source is "thick" or overlayed with some adsorbed molecules. The latter explanation is made probable by the fact that, every time a source gives results similar to Fig. 3, it is also observed that the recoil ion counting rate drops steadily from its initial

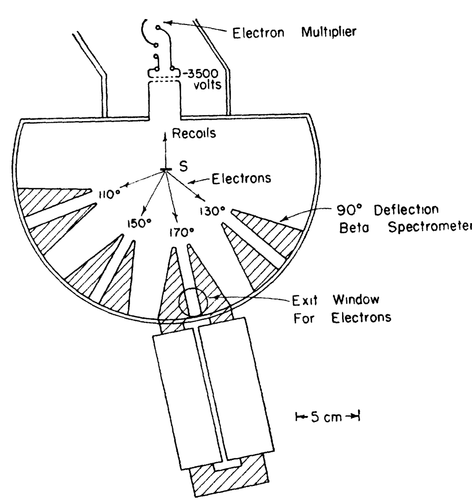

FIG. 2. Plan view of the experimental apparatus. The four beta-spectrometers are all in the same vacuum and have a common focus at the source S.

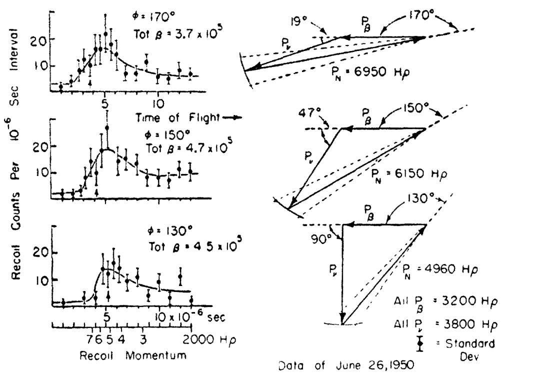

FIG. 3. Time of flight of recoil ions from a poor source. The short arrows along the time axis show where peaks of recoil ions should occur if the predictions based on the vector diagrams are fulfilled. The dotted lines bounding P_N show the over-all angular resolution set by the slit systems.

rate. This decrease in the recoil ion counting rate is noticeable in 20 min to one hour, and continues for many hours or even days before reaching a steady value of 30 to 70 percent of the initial rate. Since it takes 10 to 20 hours to observe enough events to reach any conclusions about the recoil spectra, the nature of the surface during the first hour or so of its existence is not known. This adsorbed contamination may be chemically bonded, since even violent heating by the radiant heater does not drive it off.[3]

For the "good" surfaces, shortly to be described, the recoil ion counting rate is always observed to be constant for days at a time (except for the normal beta-decay).

Many efforts at making a surface resulted in too weak an activity, so that even in 5 or 10 days of observation no significant results were obtainable.

Some surfaces were too intense. This causes the coincident events to sink down into the background; and although the statistical accuracy increases, systematic errors become enormously important. Most of the good data were obtained when the true events were 3 to 30 times the random background.

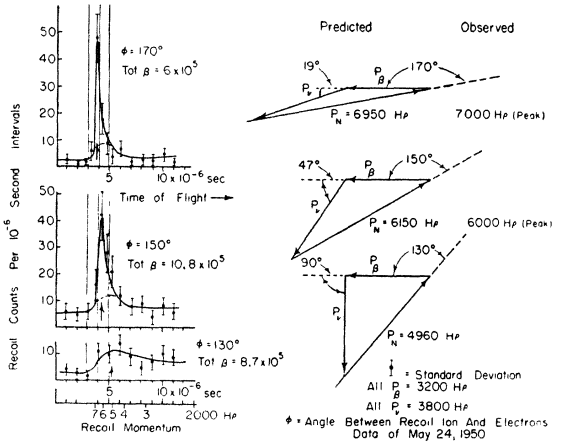

FIG. 4. Recoil ions from a good source. Superimposed on the background due to chance events and to badly scattered ions, there are sharp groups of recoil ions which occur at times that are quantitatively in agreement with the neutrino hypothesis. The short arrows on the time of flight axis show where the peaks are expected. The failure to observe a peak at 5.3 μsec for the 130° case is probably due to the weakness of the neutrino radiation at 90° with respect to the electron.

IV. SOME RESULTS WITH GOOD SOURCES

The recoil time of flight spectra for two "good" surfaces are shown in Figs. 4 and 5. Here one still sees the background of badly scattered recoil ions which seems to be much the same for all directions of electrons. However, superimposed upon this background are peaks of recoil ions which are nicely accounted for

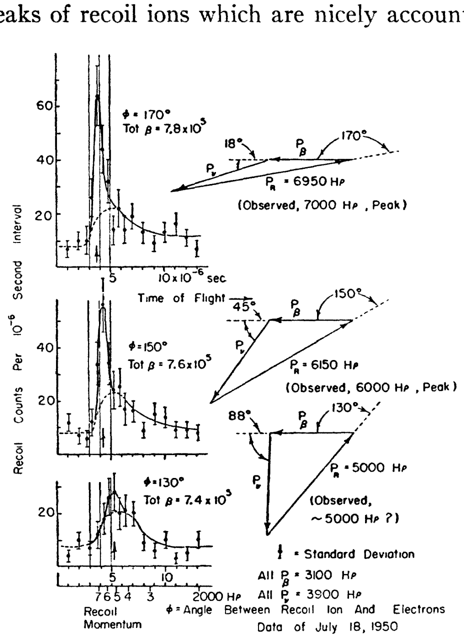

FIG. 5. Recoil ions from a second good source. Here the background of badly scattered recoil ions is much higher than for the source in Fig. 4; but fairly sharp groups of recoil ions, coming at the times predicted by the neutrino hypothesis, are clearly visible.

by the electron and the neutrino. The most convincing thing about these peaks is that they come exactly at those times, predicted by the accompanying vector triangles, which are based simply on the conservation of momentum and energy. The shift of the peak from the 170° case to the 150° case (from 3.75 to 4.25 μsec) is very clear. This shift of 0.5 μsec is much larger than either the relative or absolute experimental errors, which are both less than 0.1 μsec. The peak at 130° is so weak that its existence is uncertain. It does serve to set up some upper limit to the intensity of neutrino radiation at 90° with respect to the electron.

In order to work with still higher neutrino energies, we turn to electrons of only 2150-oersted-cm momentum. Figure 6 shows the results from the best surface that was obtained under these conditions. The experimental

[3] Diffusion into the surface is also a possibility. See H. Frauenfelder, Helv. Phys. Acta **23**, 347 (1950).

difficulties are greater than for the 3150 $H\rho$ electrons in Figs. 4 and 5, since there are fewer electrons at this energy, and also since the neutrino must enter a smaller solid angle to make an observable recoil ion. However, we again obtain agreement with the predictions of the neutrino hypothesis within experimental error. A peak of recoil ions due to neutrinos which are emitted at 70° with respect to the electrons is definitely observed. The recoil ions caused by these neutrinos have a momentum only 17 percent smaller than those recoil ions for which the electron-neutrino angle is 15°. One has some confidence, therefore, that their much lower intensity is due to the weakness of the neutrino radiation at wide angles with respect to the electron. Here v/c for the electron is 0.78, so that any angular correlation due to relativistic effects is not greatly reduced. The average scattering of the electrons as they pass through the 400 $\mu g/cm^2$ glass film is less than 3°, using the data of Groetzinger, Berger, and Ribe[4] for scattering in argon. This is less than half of the angular resolution of 8° set by slit widths.

A further advantage in using larger neutrino energies is that the solid angle corrections which are necesssary to compute the electron-neutrino angular correlation become nearly the same for the different angles involved.

V. THE ANGULAR CORRELATION OF ELECTRONS AND NEUTRINOS

The experimental angular correlation of electrons and neutrinos is shown in Fig. 7. The neutrino intensity is inferred from the intensity of the recoil ion groups after correction is made for the solid angles involved. This correction is nearly the same for all the points in Fig. 7, and therefore can introduce little relative error. The interpretation of these data in terms of beta-decay theory will be discussed in the next section. Meanwhile, it suffices to note that the experimental points are fitted adequately by an angular correlation of the approximate form $(1+\cos\theta)$.

This same conclusion was reached by earlier experiments,[1] where the correction for the effects of surface scattering was made by an indirect method. Also, the earlier experiments differed from these in that the recoil ions, which were used to infer the neutrino intensity at wide angles with respect to the electron, had much lower momenta than they do here. Thus, the refinement of the beta-spectrometer apparatus, the simple and direct method of correcting for the badly scattered recoil ions, and the use of the highest possible recoil ion momenta all confirm the conclusions reached earlier by more tenous reasoning from less reliable data.

Statistical errors are indicated in Fig. 7. Systematic errors cannot be determined exactly. The most likely source of error arises from the fact that the recoil ion groups on which the neutrino intensity is based do not all have the same momentum for different directions of the neutrino with respect to the electron. That this source of error is probably not significant is shown by the fact that the recoil ion momenta vary over a range of 17 percent in the upper part of Fig. 7, 28 percent in the lower part of Fig. 7, and 50 percent in the data of the previous paper; but all give the same result regarding the electron neutrino angular correlation. Furthermore, even though the intensity of the badly scattered recoil ions varies widely (Figs. 4 and 5), one still obtains the same angular correlation for the electron and the neutrino.

The fraction of the total recoil ions that escape the surface with little scattering is really quite small. About 1 percent of the total expected number are actually observed in the sharp peaks due to unscattered ions.

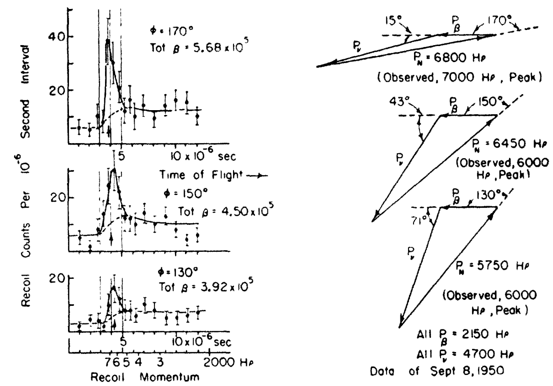

FIG. 6. Recoil ions from a third good source. Here the neutrino has over two times the momentum of the electron. The short arrows on the time axis indicate the predicted times at which the recoil ion peaks should occur. The recoil ions associated with neutrinos going at 71° with respect to the electrons have a momentum only 17 percent smaller than those associated with neutrinos going at 15° with respect to the electron.

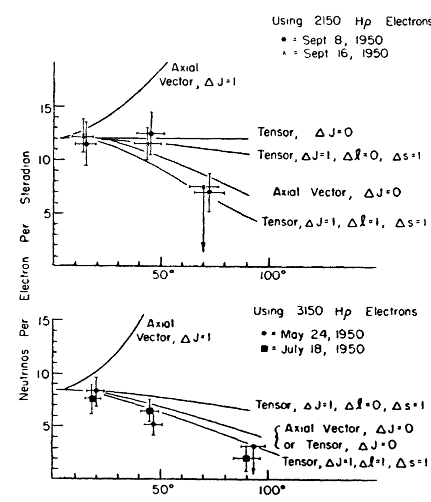

FIG. 7. The experimental neutrino-electron angular correlation for P^{32}. The error limits plotted are statistical. Only the tensor interaction with $\Delta J=1$, $\Delta l=1$, and $\Delta s=1$, and the axial vector interaction with $\Delta J=0$ agree with the observations. Each unit of the ordinate scale is 10^{-4} electron per neutrino per steradian.

[4] Groetzinger, Berger, and Ribe, Phys. Rev. 77, 584 (1950).

TABLE I. Comparison of several forms of beta-decay theory with experiment. One assumption, common to all the calculations, is that the beta-decay of P^{32} is a parity forbidden ($\pi_i = -\pi_f$) transition. If $\Delta J=1$, only the tensor interaction is in agreement with experiment; but if $\Delta J=0$, only the axial vector interaction agrees with all experimental observations. The estimates of ft values are good only to within a factor of 30 in either direction.

Form of interaction	Matrix element	ΔJ	Δl	Δs	Estimated ft value (Exp. =8.5 $\times 10^7$ sec)	Calculated beta-spectrum shape (Exp. =allowed)	Calculated electron-neutrino angular correlation. $Z=0$. Exp. $=(1+\cos\theta)$
Tensor	$\int \beta\boldsymbol{\sigma}\times\mathbf{r}$	1	1	1	5×10^7 sec	Less than 4 percent deviation from allowed Kurie plot	$[1+(v/c)\cos\theta](p^2+q^2+2pq\cos\theta)+pq(v/c)\sin^2\theta \cong 1+(4/3)\cos\theta+\frac{1}{3}\cos^2\theta$
	$\int \beta\boldsymbol{\alpha}$	1	0	1	5×10^7 sec	Allowed	$1+\frac{1}{3}(v/c)\cos\theta$
Axial vector or A-S-P	$\int \boldsymbol{\sigma}\times\mathbf{r}$	1	1	1	5×10^7 sec	Easily observable deviation from allowed	$[1-(v/c)\cos\theta](p^2+q^2+2pq\cos\theta)-pq(v/c)\sin^2\theta \cong (1-\cos^2\theta)$
Tensor	$\int \beta\boldsymbol{\sigma}\cdot\mathbf{r}$	0	1	1	5×10^7 sec	Easily observable deviation from allowed	$[1-(v/c)\cos\theta](p^2+q^2+2pq\cos\theta)-2pq(v/c)\sin^2\theta=$ constant for $p=2150$ $H\rho$ and $\cong(1+\cos\theta)$ for $p=3140$ $H\rho$.
Axial vector or A-S-P	$\int \gamma_5$	0	0	0	5×10^7 sec	Allowed	$[1+(v/c)\cos\theta]$
	$\int \boldsymbol{\sigma}\cdot\mathbf{r}$	0	1	1	5×10^7 sec	Less than 4 percent deviation from allowed Kurie plot	$[1+(v/c)\cos\theta](p^2+q^2+2pq\cos\theta)+2pq\sin^2\theta \cong (1+\cos\theta)$

About 10 percent of all those that should be available, judging from the beta-activity, are badly scattered. These are "smeared" in both time and angle and are easily distinguished, since they merely raise the background somewhat. The remaining 90 percent or so of the recoil ions probably never escape at all from what must be, on an atomic scale, a fantastically rough surface of aluminum, lithium fluoride, and impurities evaporated along with the P^{32}.

VI. THE INTERPRETATION OF THE ANGULAR CORRELATION

For the interpretation of the experimental results of Fig. 7, in terms of beta-decay theory, the calculations of Hamilton,[5] and some yet unpublished work of Blatt[6] are used.

There are five different relativistically covariant interactions which transform under the Lorentz transformation as a scalar, vector, tensor, axial vector, and pseudoscalar. These are commonly denoted by S, V, T, A, and P, respectively. Any linear combination of these five interactions is possible, but only the Wigner-Critchfield interaction[7] (A-S-P) has independent theoretical support. Furthermore, only the tensor, the axial vector, and the Wigner-Critchfield interactions require the Gamow-Teller selection rules[8] for allowed transitions. Since there is considerable evidence that these selection rules are obeyed for allowed transitions, only T, A, and A-S-P will be considered in detail. Also, these choices are in agreement with the electron-neutrino angular correlation for the allowed He^6 decay as measured by Allen.[9]

The interpretation hinges on the spin and parity of P^{32} and the daughter nucleus S^{32}. The final nucleus, S^{32}, has a measured spin of zero.[10] Since P^{32} is an odd-odd nucleus, it must have an integral spin.

P^{32} cannot have a spin of two or greater, since this would cause the beta-spectrum to have an easily observed deviation from the experimentally measured allowed shape.

We are thus left with the possibility that the spin of P^{32} is either one or zero.

There are three experimental observations which must be predicted correctly by the successful form of the theory: (1) the ft value[8] (experimentally 8.5×10^7 sec), (2) the shape of the beta-spectrum (experimentally allowed),[11] and (3) the electron neutrino angular correlation (experimentally, $1+\cos\theta$). Table I lists the interactions with their theoretical predictions regarding these three items. We have assumed that the transition must be parity forbidden ("yes") in order to account for the long half-life of P^{32}.

It should be realized however that an allowed transition with an unusually small matrix element is a possibility. The square of the matrix element would have to be about 1000 times smaller than usual for the allowed but unfavored transitions. In addition, the experimental electron-neutrino angular correlation, Fig. 7, disagrees with both the allowed tensor inter-

[5] D. R. Hamilton, Phys. Rev. **71**, 456 (1947).

[6] The relevant formulas will appear as part of a book on nuclear physics by V. Weisskopf and J. Blatt (to be published by John Wiley and Sons, Inc., New York, 1951).

[7] C. L. Critchfield and E. P. Wigner, Phys. Rev. **60**, 412 (1941); **63**, 417 (1943).

[8] E. J. Konopinski, Revs. Modern Phys. **15**, 209 (1943). G. Gamow and C. L. Critchfield, *Theory of Atomic Nucleus and Nuclear Energy Sources* (Oxford University Press, 1949).

[9] Allen, Paneth, and Morrish, Phys. Rev. **75**, 570 (1949).

[10] E. Olsson, Z. Physik **100**, 656 (1936).

[11] The excess of electrons below 300 kev observed by H. M. Agnew, Phys. Rev. **77**, 655 (1950), and also by Warshaw, Chen, and Appleton, Phys. Rev. **80**, 288 (1950) is unexplained; but in any case the spectrum shape above 300 kev is indistinguishable from the allowed form.

action $(1+(v/c)\frac{1}{3}\cos\theta)$ and with the allowed axial vector interaction $(1-(v/c)\frac{1}{3}\cos\theta)$.

The Wigner-Critchfield interaction (A-S-P) is grouped with the pure axial vector, since for this case the A term dominates (i.e., it has an appreciably smaller ft value than the S or the P terms). The exact shapes of the various theoretical angular correlation functions are plotted in Fig. 7, using the exact values of p the electron momentum, q the neutrino momentum, and v/c, where v is the electron velocity. It should be noted that in Table I the estimates of the ft values are good only to a factor of 30 in either direction.

If the spin of P^{32} is one, the tensor interaction gives agreement with all the experimental facts, but only if the $\int\beta\boldsymbol{\sigma}\times\mathbf{r}$ matrix element dominates, since the $[1+(\frac{1}{3})(v/c)\cos\theta]$ angular correlation is improbable. For this same case, the axial vector interaction can be ruled out conclusively on two counts: the beta-spectrum shape, and the angular correlation.

If the spin of P^{32} is zero, only the axial vector (or the A-S-P) interaction gives agreement with the experimental facts. For this case, the tensor interaction is ruled out on both the beta-spectrum shape, and also the electron-neutrino angular correlation observed with 2150 oersted-cm electrons. Curiously enough, for the 3150 oersted-cm electrons, the tensor interaction predicts approximately a $(1+\cos\theta)$ correlation. Because of this fact, and because even for 2150 oersted-cm electrons the theoretical angular correlation is only a constant, the tensor interaction is not as convincingly rejected for this case as is the axial vector interaction for the case where the spin of P^{32} is one.

The theoretical angular correlation functions in Table I are all calculated for the case where $Z=0$. Rose[12] has shown that for $\Delta l=0$ transitions at least, there is no appreciable effect of the nuclear charge on the angular correlation. It would be very valuable to have exact information regarding possible coulomb effects on $\Delta l=1$ transitions.

Thus, it appears that if the spin of P^{32} is one, it is fairly certain that the tensor interaction dominates the transition; and if the spin is zero, it is very probable that the axial vector interaction dominates.

VII. THE RELATIONSHIP OF THE ENERGY AND MOMENTUM OF THE NEUTRINO

Since these experiments measure both the missing energy and the missing momentum in the beta-decay of P^{32}, it is interesting to see how they are related. A few representative points out of many separate observations are plotted in Fig. 8. If all the experimental data are included, the theoretical relationship, $p=E/c$, is verified to an accuracy of 10 percent or better, the limit being set by the possibility of systematic errors. Only the statistical uncertainties are indicated in the figure. It is interesting that this law is obeyed equally well for neutrinos which make an appreciable angle with respect to the electron as well as those which go in the same direction. Since the minimum energy of the neutrinos used in these experiments is of the order of 0.5 Mev, one can draw no inferences regarding the rest mass of the neutrino, which is known, from other measurements, to be very much smaller than this.

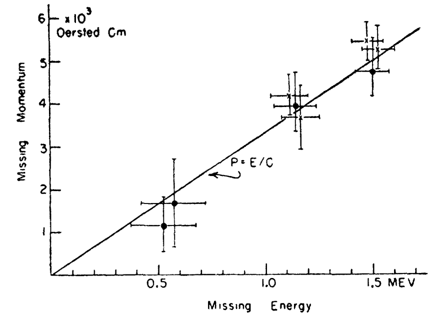

FIG. 8. The experimental relationship between the missing energy and the missing momentum in beta-decay, compared with the fundamental relativistic equation. The points indicated by circles are for cases where the missing momentum goes in nearly the same direction as the electron. The points indicated by x are for cases where the missing momentum goes 50° to 70° with respect to the electron.

VIII. CONCLUSIONS

The neutrino energy and momentum are related by $p=E/c$ to an accuracy of better than 10 percent for neutrino energies above 0.5 Mev.

For P^{32}, the electron and neutrino strongly favor the same hemisphere, having an angular correlation of the approximate form $(1+\cos\theta)$.

Adequate agreement with all the experimental data on P^{32} (the energy and half-life, the beta-spectrum shape, and the electron-neutrino angular correlation) is attained if one assumes that the spin of P^{32} is one and that the tensor interaction ($\int\beta\boldsymbol{\sigma}\times\mathbf{r}$ matrix element) dominates the beta-decay process.

Agreement with experiment is also obtained if the spin of P^{32} is zero and the axial vector interaction dominates the beta-decay process (matrix elements $\int(\mathbf{r}\cdot\boldsymbol{\sigma})$ and $\int\gamma_5$).

An experimental measurement of the total angular momentum of the P^{32} nucleus could determine uniquely whether the axial vector or the tensor interaction dominates the beta-decay of P^{32}.

The author is greatly indebted to Professor John Blatt for several valuable discussions and for the use of his calculations which apply the general beta-decay theory to the special case of P^{32}.

The author is also indebted to the Oak Ridge National Laboratory for the numerous shipments of carrier free material which made the experiments possible.

[12] M. E. Rose, Phys. Rev. **75**, 1444 (1949).