REVIEWS OF MODERN PHYSICS VOLUME 20, NUMBER 1 JANUARY, 1948

The Energy and Momentum Relations in the Beta-Decay, and the Search for the Neutrino

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INTRODUCTION

NOT everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say there is hardly one of us who is not served by the neutrino hypothesis as an aid in thinking about the beta-decay process. The neutrino, when introduced by Pauli in 1933, was assigned to the role of carrying away the missing energy, momentum, and spin in the beta-disintegration, making it possible to retain the conservation laws. While the hypothesis has had great usefulness, it should be kept in the back of one's mind that it has not cleared up the basic mystery, and that such will continue to be the case until the neutrino is somehow caught at a distance from the emitting nucleus. Some physicists prefer to say simply that energy and momentum are apparently not conserved, giving full recognition, of course, to the energy and momentum relations that have been established experimentally, and to the successes of the beta-ray theory which has been built upon the neutrino hypothesis. Perhaps all one can say is that this is a matter of taste. Certainly the body of experimental evidence has pretty well narrowed the possibilities down to a neutrino hypothesis of some kind, as the only alternative to the more non-committal view just mentioned. What we cannot be so sure of is that any experimental justification can yet be found for the assumption that there is a unique neutrino and that just one of these is emitted in each beta-disintegration. As we shall see in the review which follows, answers to these questions are now within reach, experimentally. There are many interesting aspects to the "case" when examined as a whole, and it is my hope that this review may be of some benefit in the planning of future attacks on the problem. Needless to say, no attempt will be made to enter into a discussion of the beta ray theory, which, with its many variations, constitutes a literature in itself, and which has been reviewed recently in this journal.[1]

THE ENERGY RELATIONS

Evidence that the Energy Lost by the Nucleus Corresponds to the Upper Limit of the Beta-Spectrum, Regardless of the Energy of the Electron Emitted

The classical argument which is found in the literature makes use of the branching in the natural radioactive series, particularly the $ThC \rightarrow C' \rightarrow D$, $ThC \rightarrow C'' \rightarrow D$ branch. Ellis[2] has shown that the alpha-, beta- and gamma-energies, when added along the two branches, give the same sum only if the upper limits are used for the beta-decays, and not if the average energies of the beta-spectra are used. More clear-cut proofs can now be found by turning to the reactions of the light elements. The best ones are the closed cycles in which a p-n reaction is followed by positron emission. Haxby, Shoupp, Stephens, and Wells[3] have investigated the energy thresholds for the reactions

$$B^{11}+p \rightarrow C^{11}+n; \quad C^{11} \rightarrow B^{11}+e^{+}+\nu,$$
$$C^{13}+p \rightarrow N^{13}+n; \quad N^{13} \rightarrow C^{13}+e^{+}+\nu.$$

It is clear that the energy of the bombarding proton at threshold, the neutron-proton mass difference, and the mass of the electron are the only quantities that have to be known in order to find the energy available for the beta-disintegration. The values found for C^{11} and N^{13} are 0.95 ± 0.02 and 1.20 ± 0.04, respectively. The best available measurements of the upper limits of the beta-ray spectra give 0.95 ± 0.05[4] and 1.198 ± 0.006[5] for C^{11} and N^{13}, respectively. This

[1] E. J. Konopinski, Rev. Mod. Phys. 15, 209 (1943).
[2] C. D. Ellis, Internat. Conf. on Physics, London, 1934.
[3] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. 58, 1035 (1940).
[4] L. A. Delsasso, M. G. White, W. Barkas, and E. C. Creutz, Phys. Rev. 58, 586 (1940).
[5] E. M. Lyman, Phys. Rev. 55, 234 (1939).

is very satisfying support for the idea that the energy lost by the nucleus is that corresponding to the upper limit of the spectrum, rather than, say, the mean. Although the cyclical type of reaction is given because of its simplicity and accuracy, it should be emphasized that there are many reactions for which the energy balance is known with sufficient accuracy for the purpose discussed here. B^{12} would be a striking example to use, because of the great difference (about 7 Mev) between the upper limit and the mean of its spectrum, but its use will have to await a precise determination of its mass, through the study of the reactions leading to its formation.

The Mass of the Neutrino

The approximate equality between the energy lost by the nucleus (from its mass change) and the upper limit of the beta-ray spectrum was used as the number one argument in favor of postulating the existence of a neutrino. Now an attempt can be made to use whatever small discrepancy remains between these values to ascertain the apparent rest mass of the neutrino. In order to do so one has, inescapably, to assume a shape for the spectrum in the neighborhood of the upper limit, in order to determine the intercept, because the number of electrons just at the upper limit is vanishingly small. Drawing a curve through the points "by eye" does not avoid the trouble because the experimental uncertainty increases as the upper limit is approached and the shape of the curve used is still arbitrary. On the other hand, the shape given by the Fermi beta-ray theory may be used and a precise value of the intercept found. The operation requires successive approximation because the shape of the curve near the upper limit, given by the theory, depends upon the mass of the neutrino.[6] The two methods give intercepts which agree very well, but it should not be forgotten that identifying the intercept found in either way, with the case in which the electron has all of the energy and the neutrino none, is based upon an assumption.

The energy balances which give the most reliable estimates of the neutrino mass are those already mentioned, which are obtained from the cyclical systems $B^{11}(p,n)C^{11}$; $C^{11}\rightarrow B^{11}+e^{+}+\nu$ and $C^{13}(p,n)N^{13}$; $N^{13}\rightarrow C^{13}+e^{+}+\nu$. These give 0.001 ± 0.056 and 0.0 ± 0.07 Mev, respectively, for the energy equivalent of the mass of the neutrino. About all that can be concluded is that the mass is considerably smaller than that of the electron.

Although it is not the intention here to introduce theoretical arguments, the recent work of Konopinski[7] should be mentioned. He calls attention to the fact that the beta-ray spectrum of H^3 has such a low energy (11 ± 2 kev) that a theoretical calculation of the lifetime should be extremely sensitive to the neutrino rest mass. He finds that a mass of 1/30 to 1/45 of the electron mass brings the theoretical lifetime into agreement with the measured value, while zero mass leads to a discrepancy of a factor 10.*

The Identity of Beta-Rays with Ordinary Electrons

It has been a long time since anyone has questioned the idea that the beta-rays are identical with ordinary electrons. A slight ripple of doubt in 1937–38 prompted the repetition, with refinements, of some of the experiments, and the subject has been quiescent since. It seems safe to discard immediately the possibility that the beta-particle could have enough extra mass to account for all of the missing energy in the beta-decay process. This would call for such an enormous increase in the mass of those particles from the lower end of the spectrum that the effect would stand out, experimentally, like the proverbial sore thumb. But a more pointed question is whether or not experiments can exclude the possibility that, for example, the spin of the beta-particle is different from one-half unit, with only a slight effect upon the mass. This kind of question should be answered as precisely as possible for the record, and therefore the experimental facts which seem to be most pertinent will be cited here. The ratio e/m for beta-rays was measured by Bucherer[8] in 1909

[6] O. Kofoed-Hansen, Phys. Rev. **71**, 451 (1947).

[7] E. J. Konopinski, Phys. Rev. **72**, 518 (1947).

* *Note added in proof.* Two abstracts giving further information on this point have appeared recently: J. R. Pruett, Bul. Am. Phys. Soc., Chicago Meeting, Dec. 29–31, 1947, A3; D. J. Hughes and C. Eggler, Bul. Am. Phys. Soc., Annual Meeting, Jan. 29–31, 1948, D8.

[8] A. H. Bucherer, Ann. d. Physik **28**, 513 (1909).

and by Neumann[9] in 1914, by the classical method of deflecting the particles in crossed electric and magnetic fields—the method used in virtually all mass spectrometers. Zahn and Spees[10] made experiments of the same kind in 1937–38, and introduced important refinements over the earlier technique. In particular they made improvements which eliminated the objection that many of the electrons (perhaps all) observed by Bucherer and by Neumann could have been secondaries, knocked out of the metal parts of the apparatus by the primary beta- and gamma-rays. Zahn and Spees found a single sharp line which agreed with the electronic e/m ratio, within a probable error of 1.5 percent. Next, two facts may be cited which carry exceedingly strong conviction that beta-particles are ordinary electrons: first, the fact that orbital electrons can participate in the beta-decay process through *K*-capture; second, the fact that positively charged beta-particles annihilate with ordinary electrons when stopped. Both of these effects take place completely in accord with theory, on the assumption that beta-rays are ordinary electrons. In particular, the excellent agreement between the observed and calculated lifetime for the *K*-capture process should be noted, because this is one of the special successes of the present-day theory.

To round out the argument, it would be gratifying if one could show the identity of electrons and beta-particles from experiments on their scattering and stopping in matter. One immediately finds that little of the existing scattering work is of any use in this connection, because the collisions are not close enough to show anything beyond Rutherford scattering. The only outcome is a comparison of the e/m ratio, which is far more accurately given by other methods. An idea as to what the conditions of scattering would have to be to show a reasonable sensitivity to the spin of the particle can be obtained by making use of the calculations of Pauli[11] on the scattering of mesons in the Coulomb field of a nucleus. Evaluating his formulae for particles of electronic mass and magnetic moment, and 5-Mev energy, it appears that the scattered intensity at 90 degrees would be about 15 percent greater for particles of spin 1 than for electrons (spin $\frac{1}{2}$). These are about the most favorable conditions, and the difference is a little smaller than the experimental error in the existing experiments. The recent experiments of Buechner *et al.*,[12] on the scattering of accelerated electrons, have the necessary accuracy, but those of Randels, Chao, and Crane,[13] and of Bleuler, Scherrer, and Zunti,[14] which appear to be the most suitable of the experiments using beta rays from radioactive sources, fall just short of having sufficient accuracy.

THE MOMENTUM RELATIONS: RECOIL EXPERIMENTS

General Discussion

All of the evidence about the neutrino is, as already pointed out, indirect in character, since neutrinos have not yet been caught after leaving the nucleus. But of all the pieces of evidence the measurement of the recoil of the nucleus seems to be the most appealing, at least to our pictorial senses. It can, of course, be argued on very general grounds that, if energy is not conserved between the nucleus and the electron, momentum should not be expected to be conserved either; and in consequence of this it has often been remarked that the recoil experiments add nothing that is really new to our knowledge. It can be shown, however, that the recoil experiments do give information that cannot be obtained in any other way. First, the picture in which the missing energy escapes in a single package (neutrino) was first adopted because it was the simplest picture, and later it was made to seem more real because of the successes of beta-decay theories which were based upon it. The more complicated picture of the nucleus frittering away its excess energy in a number of packages, all at once or within a finite length of time (10^{-4} sec. or so) should not be overlooked just because of the theoretical success of the simpler hypothesis. It is not hard to imagine that a successful theory

[9] G. Neumann, Ann. d. Physik **45**, 529 (1914).

[10] C. T. Zahn and A. H. Spees, Phys. Rev. **52**, 524 (1937); **53**, 357 (1938); **53**, 365 (1938).

[11] W. Pauli, Rev. Mod. Phys. **13**, 203 (1941).

[12] W. W. Buechner, R. J. Van De Graaff, A. Sperduto, E. A. Burrill, Jr., and H. Feshbach, Phys. Rev. **72**, 678 (1947).

[13] R. B. Randels, K. T. Chao, and H. R. Crane, Phys. Rev. **68**, 64 (1945).

[14] E. Bleuler, P. Scherrer, and W. Zunti, Phys. Rev. **61**, 95 (1942).

could have been constructed also on a multiple neutrino hypothesis. Neither can the latter be discarded by existing experiments, other than those on recoil. The measurement of the recoil in a K-capture process is the one experiment which can distinguish sharply between the emission of single and multiple neutrinos. If the single neutrino picture is correct, the momentum spectrum of recoils will be a line spectrum since the energy of the transformation is not shared between an electron and a neutrino but is taken by the neutrino alone. If no gamma-rays are emitted, the recoil spectrum will consist of a single line. In contrast, the multiple neutrino picture would, clearly, give a continuous distribution of recoil momenta. Second, recoil experiments can tell something about the angular correlation between the directions of emission of the electron and the neutrino. Theoretical predictions for the angular correlation were first worked out by Bloch and Moller,[15] and recently a paper giving the predictions for all the different interactions has been published by Hamilton.[16] For allowed transitions the correlation function is $W(\theta)=1+\alpha(p/E)\cos\theta$ where p is the electron momentum in units mc and E is the total electron energy in units mc^2; $E^2=p^2+1$. α has values -1, 1, $\frac{1}{3}$, $-\frac{1}{3}$ and -1, respectively, for the simple scalar, polar vector, tensor, axial vector, and pseudo-scalar interactions. The results are more complicated for first forbidden transitions and will not be given here. The point which Hamilton emphasizes is that the angular correlation changes much more, from one interaction to another, than does the shape of the beta-ray spectrum. Consequently recoil experiments have something to offer in this direction which cannot be obtained as well in other ways.

As it turns out, experimentally, the answers to the two questions, single or multiple neutrinos, and angular correlation, are not interdependent. The K-capture experiment can answer the first, without regard to the second; then if we are assured by this that single neutrinos are emitted, we can proceed to the non-K-capture experiments to obtain the angular correlation.

Experiments on the measurement of the recoil in the ordinary beta-decay yield various kinds of information, in some cases little beyond the demonstration that momentum is apparently missing. When only the recoil momentum spectrum is measured, the angular correlation cannot be found directly, and the best that can be done is to compare the observed spectrum with that computed on various theoretical assumptions. Where one additional quantity is measured, such as the energy of the electron or the direction of the electron with respect to that of the nucleus, the neutrino-electron angular correlation can in general be constructed from the data, on the assumption, of course, that energy is conserved and that single neutrinos are emitted. In one case (the disintegration of Li^8 in a cloud chamber) enough quantities can be measured, in principle, so that the directions and momenta of all particles can be found without relying upon the auxiliary information supplied by the K-capture experiment. It should be understood that in all of the foregoing discussion a mass small compared to that of the electron has been assumed for the neutrino. In the following paragraphs the recoil experiments which have been done to date will be discussed individually.

[15] F. Bloch and C. Moller, Nature **136**, 911 (1935).
[16] D. R. Hamilton, Phys. Rev. **71**, 456 (1947).

Recoil Experiments Using the K-Capture Process

1. The best K-capture isotope available at present for recoil experiments is Be^7. Its use was first suggested by Kan Chang Wang[17] and an experiment was completed only a few months later by Allen.[18] Be^7 has been investigated by Rumbaugh, Roberts, and Hafstad.[19] They found that it is formed according to the reaction

$$Li^6+D^2\rightarrow Be^7+n \quad (3.3\text{ Mev}),$$

and that it decays in two ways, 90 percent according to

$$Be^7+e_K\rightarrow Li^7+\nu \quad (1\text{ Mev}),$$

and 10 percent according to

$$Be^7+e_K\rightarrow Li^{7*}+\nu \quad (0.55\text{ Mev}),$$
$$Li^{7*}\rightarrow Li^7+\gamma \quad (0.45\text{ Mev}).$$

[17] Kan Chang Wang, Phys. Rev. **61**, 97 (1942).
[18] J. S. Allen, Phys. Rev. **61**, 692 (1942).
[19] L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).

Haxby, Shoupp, Stephens, and Wells[20] later gave 0.87 Mev for the difference between Be^7 and Li^7 instead of 1 Mev. If the latter value is accepted, and zero mass is assumed for the neutrino, 90 percent of the recoils should have 58 ev energy. In the case of the remaining 10 percent, the recoil energy is given in two parts (escape of the neutrino and then the gamma-ray) within a time which is almost surely short compared with the time required for the recoil energy to be dissipated by atomic collisions in the substrate. Therefore the 10 percent will contribute a continuous distribution of recoil energies from 58 ev down to nearly zero. There is the further possibility (although this would be expected to be rare) that the neutrino is followed by internal conversion, giving a maximum possible recoil energy of 105 ev. Allen did not assume that the recoils from the 10 percent fraction would have other than 15.6 ev, which is the recoil energy to be expected from the gamma-ray alone, but the question is of minor importance to the results.

In Allen's, as in several of the other experiments the crucial part of the process is the escape of the recoil atom from the substrate on which the radioactive material has been deposited. A great share of Allen's success is due to his wise choice of platinum for the substrate. First, the work function of platinum is less than the first ionization potential of lithium. This causes the lithium recoils to be ionized upon leaving the surface. Second, by heating the platinum, the lithium can be driven off, leaving the Be^7 within a small depth near the surface (during the heating it diffuses into the platinum somewhat). Third, the platinum itself can be slowly etched away by evaporation, leaving freshly exposed Be^7 at the surface. This is done just prior to the measurement of the recoils. The rest of Allen's method was fairly straightforward: the ionized recoils were subjected to a retarding electric field which let through only those which had left the platinum surface with greater than some chosen value of energy. Those which passed through were then accelerated to several kev energy and allowed to strike the first electrode of an electron multiplier tube which counted them.

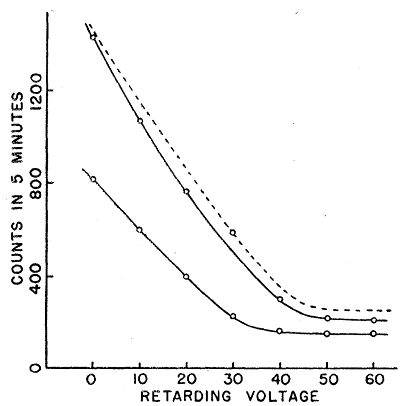

Fig. 1. The experimental curves obtained by Allen. The upper solid curve gives the counts from a freshly prepared source, the lower solid curve those obtained after allowing the source to age. The dotted curve represents the data corrected back to zero age for the source.

The assumption that the number of recoils due to gamma-ray emission was small was verified by a separate experiment in which a Geiger counter was added to the apparatus, which measured the number of gamma-ray counts which were coincident in time with recoil counts.

The main results of Allen's experiment are contained in the curve shown in Fig. 1, reproduced from his paper. This is a strikingly clear demonstration of the existence of recoil momentum of approximately the amount called for by the neutrino hypothesis. The actual values of the upper limits of the recoil curves are 10 to 15 volts lower than expected, but this does not seem to be a surprising discrepancy in view of the uncertainties involved. Allen points out that several volts of this may be accounted for by the work function of the surface for the lithium ions. Assuming a small rest mass instead of zero for the neutrino has little effect upon the results: a mass of 0.2 that of the electron would lower the maximum recoil energy by only 1 ev. An uncertainty in the Be^7-Li^7 mass difference would be important, since the upper limit of the recoil spectrum varies as the square of this difference. The probable error attached to the Be^7-Li^7 difference is only two or three percent, however, so it is difficult to assign more than 5 percent of the discrepancy in the recoil spectrum to this cause. The circumstances surrounding the escape of the recoil from the substrate seem to offer the most fertile possibilities for accounting for the

[20] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. 58, 1035 (1940).

discrepancy; for example, there may always be a monomolecular layer of gas covering the radioactive material.

I have already pointed out that the most direct way to prove that the missing energy is carried away by a single neutrino would be to show that the recoils in the K-capture were monoenergetic. This is not shown by Allen's results. Two effects may be mentioned which may account for part or all of the slope of his distribution curve: (1) Diffusion of the Be^7 into the platinum during the heating process, which, as Allen points out, certainly occurs to some extent, producing a "thick source." (2) The fact that the initial direction of the momentum of each recoil may differ from the direction of the retarding field, the maximum angle depending upon the apertures used. Since only the component of momentum parallel to the retarding field is measured, an appreciable spreading of the distribution toward lower momenta may result from this cause. While these effects are capable of accounting for the difference between Allen's curve and a monoenergetic one, quantitative estimates of the corrections are difficult to present. Further experiments will have to be done to show that the recoils are mono-energetic.

2. One other K-capture experiment has been reported: that of Wright,[21] which is the continuation of some earlier work of Alvarez, Helmholz, and Wright.[22] The 6.7-hour Cd^{107} decays almost entirely by K-capture[23] to a metastable level in Ag^{107}, which in turn goes to its ground state by internal conversion with a half-life of 44.3 seconds.[24] A level scheme has been given by Bradt, *et al.*[25] (Fig. 2). The silver recoil is expected to have a 7.9-ev energy. In Wright's apparatus active cadmium was deposited by a two-stage vacuum distillation upon a clean tungsten surface. The recoil atoms (metastable Ag^{107}) which hopped off this surface were collected on a nearby tungsten surface, which was subsequently moved into position in front of a Geiger counter,

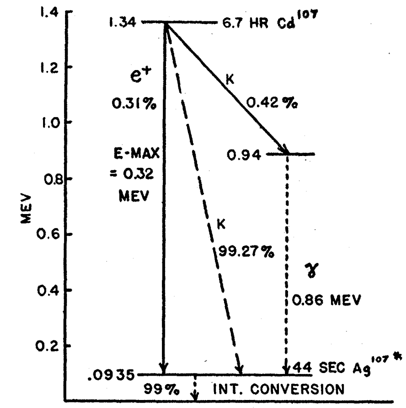

FIG. 2. The decay diagram for Cd^{107} as given by Bradt and his co-workers.

for the counting of the conversion electrons from the Ag^{107*}. The silver recoils were uncharged, therefore it was not possible to make use of a retarding field and obtain an energy distribution. Quantitative measurements showed that of all the Ag^{107*} atoms recoiling into the hemisphere available for collection, 8 percent were actually collected. This eliminated the possibility that those collected were due to the less than 1 percent of the transitions in which either a positron or a gamma-ray is emitted (Fig. 2). The energy which a neutral silver recoil must have to escape from the metal surface can be estimated reliably from the heats of vaporization of the metals involved, and is several electron volts. The maximum recoil energies obtainable from the x-rays and Auger electrons which follow the K-capture are only 0.003 ev and 0.22 ev, respectively. Therefore the fact that the recoils do escape from the surface, and that quantitatively the number collected is of the right order of magnitude, is strong evidence that momentum is acquired by the atom in accord with the neutrino hypothesis.

A few words might be said here in regard to a possible defect in all experiments in which the atom recoils from a surface following K-capture, and which Wright recognizes in his paper. It is not entirely safe to consider the atom and the neutrino as a free system, in which momentum is conserved. In the refilling of the K-orbit after K-capture, considerable energy is released (24 kev in the present case, Ag) and there is the possibility that some of this can be transformed into kinetic energy of the atom, the surface

[21] B. T. Wright, Phys. Rev. **71**, 839 (1947).
[22] L. W. Alvarez, A. C. Helmholz, and B. T. Wright, Phys. Rev. **60**, 160 (1941).
[23] A. C. Helmholz, Phys. Rev. **70**, 982 (1946).
[24] H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, P. Preiswerk, P. Scherrer, Helv. Phys. Acta **18**, 255 (1945);
[25] H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, P. Preiswerk, P. Scherrer, R. Steffen, Helv. Phys. Acta **19**, 218 (1946).

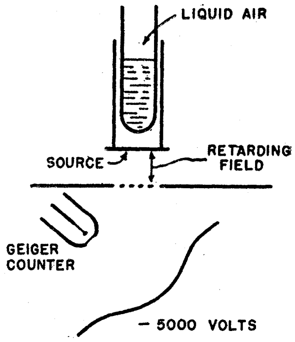

FIG. 3. Schematic diagram of the apparatus used by Leipunski.

taking momentum. This can give rise to a large "recoil" energy. A mechanism of this kind has been considered in some detail by Cooper.[26] Wright therefore found it necessary to take the precaution of measuring quantitatively the number of recoils, to answer the objection that the recoils may be due to a secondary process such as that mentioned. The same question can be asked about Allen's experiment, since the K-ionization energy of Li is about 75 ev. It is interesting to note that, in contrast, no energy is released due to the readjustment of the orbital electrons in the case of ordinary beta-decay. Hebb[27] has shown, by a simple theoretical argument that the emission of the electron and the resulting change in nuclear charge do not leave the atom in an excited state.

Experiments on Electron Emitters, in which only the Momentum of the Nucleus is Measured

1. The first attempt in history to observe the recoil of the nucleus which achieved any degree of success was that of Leipunski[28] in 1936. A diagram of his apparatus as shown in Fig. 3. C^{11}, in the form of carbon dioxide and carbon monoxide, was condensed on a surface which was maintained at liquid air temperature. It was found that at least some of the B^{11} atoms which were projected outward from the cold surface were ionized. An electric retarding field between the cold surface and the grid allowed only those recoils having greater energy than some given value to pass through the grid. On the other side of the grid the recoils were accelerated to 5000 ev and allowed to strike a low work function surface. The secondary electrons knocked out of this surface were accelerated to 5000 ev, which was enough energy to allow them to penetrate the Geiger counter window. The integral distribution curve for the recoils (number having energy greater than E plotted against E) which was found is shown in Fig. 4. For comparison, a curve is given which was calculated using the known beta-ray distribution for C^{11} and assuming a momentum of recoil equal to the momentum of the electron alone. Both calculations were made on the assumption that there was no absorption in the source.

The interpretation of Leipunski's experiment is difficult, to say the least. Almost all of the uncertainty is concerned with the escape of the B^{11} recoil ions from the surface. Since the ions are afterward accelerated to an energy that is high (5000 ev) compared to the energy of recoil, before striking the low work function surface, the possibility of the shape of the recoil spectrum being modified at this point in the chain of events is eliminated. For a similar reason the efficiency with which the secondary electrons fire the Geiger counter can have no correlation with the original recoil energy. But we may ask two further questions about the escape process. First, is the probability of escape of the recoil (ionized or non-ionized) from the surface dependent upon its energy? Probably not, for those

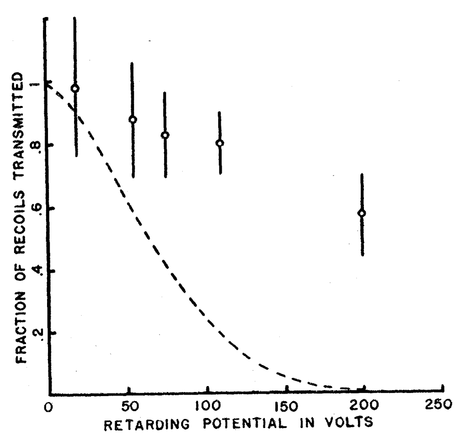

FIG. 4. Leipunski's results. The points represent the actual counts of recoil ions and the dotted curve is the distribution calculated on the assumption that the momentum of the recoil is equal to that of the electron alone.

[26] E. P. Cooper, Phys. Rev. **61**, 1 (1942).
[27] M. H. Hebb, Physica **8**, 701 (1938).
[28] Leipunski, Proc. Camb. Phil. Soc. **32**, 301 (1936).

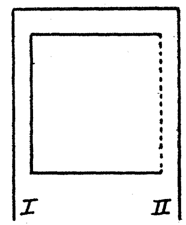

FIG. 5. Schematic diagram of the apparatus used by Jacobsen and Kofoed-Hansen. The retarding potential is applied between the outer and the inner box. Recoil ions starting from the field free space within the inner box enter the retarding field by passing through the grid (dotted line). Those having sufficient energy strike surface II and remain there.

situated in the very top layer, since the energy of binding to the surface is only a few electron volts while the energy of recoil ranges up to 180 electron volts.* However, the layer on the liquid air-cooled surface, which must include condensed vapors besides the radioactive material, almost certainly constitutes a "thick source," that is, one having a depth greater than the range of the recoils. This would tend to increase the number of recoils having small momentum. Second, does the probability that a recoil is positively charged when it leaves the surface depend upon its energy? Here we must recall that, since this is a case of positron emission, the B^{11} is born with an excess negative, not positive, charge; therefore we must look to some secondary ionizing process to account for the fact that positively charged recoils are found at all. Let us consider the possible mechanism. The work function of the underlying metal certainly is not greater than the ionization potential of the B^{11} (8.26 volts), so ionization just by contact with the metal is not a possibility. Ionization through collision of the B^{11} with other atoms in the substrate is energetically possible, since the maximum energy of recoil is 180 ev and only about 30 ev is used, on the average, in a collision ionization event. Such a process would be of low efficiency, it would favor the recoils having high energy, and worst of all, it would favor those recoils which suffer collisions and loss of energy in leaving the substrate. Unfavorable as this mechanism is, it seems to be the one most capable of explaining the existence of ionized recoils. Leipunski mentions that it was necessary to use a very strong source in order to obtain an appreciable counting rate, which would indicate either that the ionization mechanism was of an inefficient kind or that the condensed layer containing the $C^{11}O_2$ and $C^{11}O$ had a depth which was large compared to the range of the recoils. A further effect which should be noted is that, according to Leipunski's sketch of his apparatus, recoils could leave the surface with large angles to the direction of the retarding field and still be counted. This was discussed in connection with Allen's experiment; the result is, briefly, to enhance the low end of the recoil spectrum.

It seems to be futile to try to apply the corrections which would be necessary for the interpretation of the Leipunski experiment. Nevertheless the experiment had great value in that a successful method of detecting recoil nuclei was found for the first time, and the way was thereby opened for a succession of experiments on the momentum relations in the beta-decay.

2. Jacobsen and Kofoed-Hansen[29] performed an experiment which took advantage of the fact

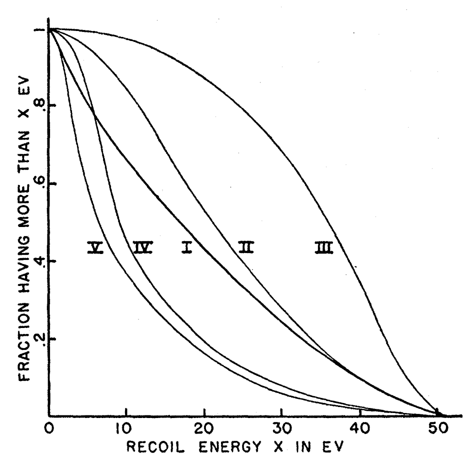

FIG. 6. The experimental and theoretical curves given by Jacobsen and Kofoed-Hansen. I, experimental; II and III, curves calculated on the neutrino hypothesis, using two different neutrino-electron angular correlation functions; IV, curve calculated on the assumption that all transitions go to the 1.4-Mev excited state of Rb^{88} and that there is no neutrino; V, curve calculated on the assumption that all transitions go to the ground state of Rb^{88} and that there is no neutrino.

* Leipunski evidently used about 200 ev as the maximum recoil energy. A calculation with the presently accepted value for the upper limit of the C'' spectrum (0.95 Mev) gives somewhat less, about 180 ev.

[29] J. C. Jacobsen and O. Kofoed-Hansen, Det. Kgl. Danske Vidensk. Selskab, Mat.-Fys. Med. **23**, paper No. 12 (1945).

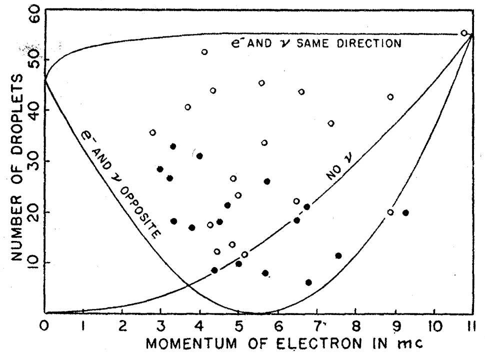

FIG. 7. The results found by Crane and Halpern. Each dot or circle represents a droplet cluster. The dots represent the data gathered in the first series of experiments (first publication) and the circles represent the second series.

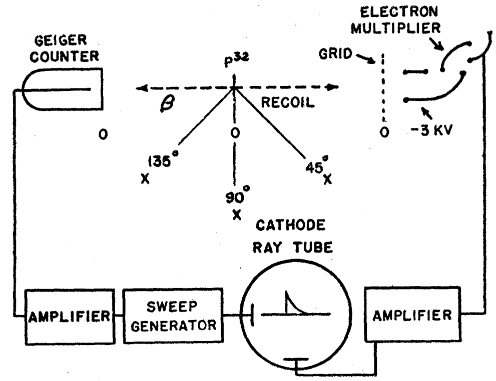

FIG. 8. Schematic diagram of Sherwin's apparatus. Other positions for the Geiger counter are indicated by X.

that in the fission of uranium a noble gas isotope, Kr^{88}, which undergoes two successive beta-disintegrations is produced. If the uranium, after irradiation with neutrons, is left for about 3 hours (to allow the short lived products to die off) before the inert gases are driven off and collected, only one isotope is found to be present which disintegrates twice, namely Kr^{88}.[30] The decay proceeds as follows:

$$Kr^{88} \xrightarrow[2.7\text{ hr.}]{2.4\text{ Mev}} Rb^{88} \xrightarrow[17.8\text{ min.}]{5\text{ Mev}} Sr^{88}.$$

By means of beta-gamma coincidence counting, it was established by Jacobsen and Kofoed-Hansen that the decay of Kr^{88} to Rb^{88} followed the scheme

$$Kr^{88} \nearrow Rb^{88}, \quad Kr^{88} \searrow Rb^{88*} \xrightarrow{\gamma} Rb^{88},$$

but owing to the complication of having other isotopes present in the counter experiments, neither the branching ratio nor the energy of the gamma-ray was found.

A schematic diagram of the apparatus for the recoil experiment is shown in Fig. 5. The gas containing the Kr^{88} is introduced at a pressure so low that the mean free path of the recoils is large compared to the dimensions of the apparatus. Recoils from anywhere within the inner box can pass through the grid, then through the retarding field. The recoils which result from the first decay and are collected on surface II decay again later, so the activity of this surface is a convenient measure of the number of recoils collected. The activity on surface *I* is a measure of the number of recoils originating within the retarding field space between the inner box and surface *I*. Since this is of the same dimensions as the space between the grid and surface *II*, and since the gas pressure and field are the same, it serves as the correction to be subtracted from the activity measured at *II*. The difference is due to recoils from the field free space in the inner box.

In principle the experiment is beautifully simple, but in practice it is not without complicating circumstances. First, a loose end has to be left hanging because almost nothing is known as to what fraction of the Kr^{88} decays to an excited level of Rb^{88} or as to the height of the excited level. In those cases in which the electron, neutrino, and gamma-ray all go in the same direction, the recoil momentum will be nearly independent of the level scheme used, so only the shape, not the upper limit of the recoil spectrum, will depend upon the level scheme. To test the effect of changing the level scheme the authors made a calculation, arbitrarily assuming that 100 percent of the Kr^{88} decayed to a 1.4-Mev excited level of Rb,[88] that no neutrino was emitted, and that the directions of emission of the beta and the gamma were not related. This was compared with the recoil distribution expected on the assumption of 100 percent decay

[30] G. N. Glasoe and J. Steigman, Phys. Rev. 58, 1 (1940).

to the ground state of Rb, again without a neutrino. The difference was small (curves IV and V, Fig. 6). This impression, that the shape of the recoil spectrum is insensitive to the level scheme assumed, is correct only so long as the beta-spectrum energy is not taken to be small compared to the gamma-ray energy. It is clear that if nearly all the energy in the decay were assigned to the gamma-ray, the recoil spectrum would approach one in which all the recoils had nearly the upper limit of energy. There is some evidence that the excited level in Rb^{88} is not higher than 1.8 Mev (beta-spectrum energy 0.6 Mev) from the fact that in the beta-gamma coincidence measurements Jacobsen and Kofoed-Hansen found that the coincidences disappeared when the beta-ray filter reached 200 mg/cm^2 of aluminum. Thus while the excited level could, if it were high enough, move curve IV up to the neighborhood of the experimental curve (I) without benefit of the neutrino, it seems to be safe to assume that it does not. It is very much to be hoped, therefore, that someone will find a way to determine the level scheme of Kr^{88}. Second, a correction was made to take into account the useful solid angle into which each point of the space in the inner box can contribute recoils which can pass through the grid. Third, the fact that a recoil which emerges from the grid at an angle to the direction of the retarding field executes a parabolic path, and that the energy it has to have to reach the collecting surface depends upon the angle of emergence, was considered. This, and the solid angle correction are difficult to treat, except by the method of first assuming an energy distribution for the recoils, making the corrections on that basis and comparing the result with the experimental curve. Instead of attempting the corrections, the authors show by a qualitative argument that the corrected curve can only lie everywhere above the uncorrected curve (I in Fig. 6) and therefore that if the corrections were made they could only strengthen the evidence for the neutrino hypothesis. (Incidentally, Jacobsen, and Kofoed-Hansen appear to be the only experimenters who have even discussed the effect of the parabolic paths of the recoils in a retarding field.) Fourth, the probability for loss of energy by the recoil due to collisions with gas atoms was calculated and found to be just small enough to be neglected. This was confirmed, experimentally, by raising the gas pressure during one of the runs. Electron capture by the recoils, either upon collision with a gas atom or with the wall, could not have been responsible for an appreciable part of the collected activity on plates *I* or *II*, as was shown by the fact that when a very large retarding field was used, the activity fell practically to zero.

Figure 6 is a composite showing the five curves presented by Jacobsen and Kofoed-Hansen. Curve I gives the experimental data. Curve IV is the distribution expected on the assumption that all transitions go to a 1.4-Mev excited state in Rb^{88}, and that there is no neutrino. Curve V is computed on the assumption that all transitions go to the ground state of Rb^{88}, and that there is no neutrino. Curves II and III are computed on the assumption that all transitions go to the ground state of Rb^{88}, that there is a neutrino of zero rest mass, and that the direction of emission of the neutrino with respect to that of the electron is given by

$$W(\theta)d\theta = \tfrac{1}{2}\sin\theta[1-(v/c)\cos\theta]d\theta$$

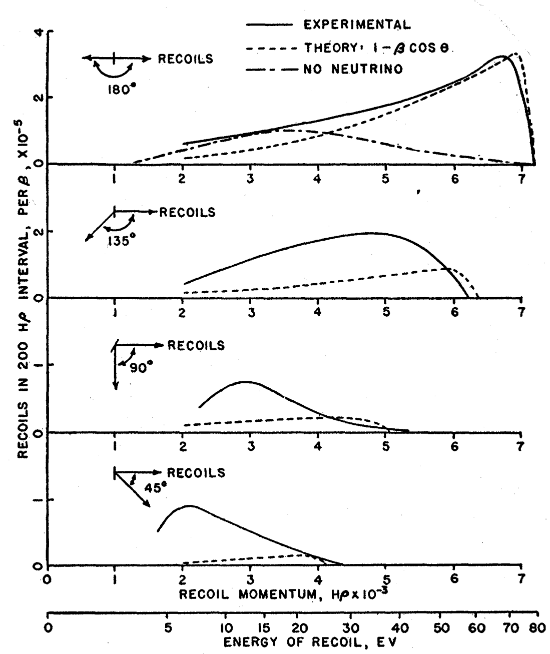

FIG. 9. Recoil momentum distributions found by Sherwin, for the four different positions of his Geiger counter. Theoretical curves are given for comparison.

and

$$W(\theta)d\theta=[1+(v/c)\cos\theta]d\theta,$$

respectively, where v is the velocity of the electron and θ is the angle made by the two directions. As to the final interpretation of the results, one can agree with the authors that the experimental curve is incompatible with the assumption that there is no neutrino, and that it is not possible to go so far as to say anything about the angular distribution in the emission of the neutrino.

Experiments on Electron Emitters in which one Quantity in Addition to the Recoil Momentum is Measured

1. Crane and Halpern[31] measured the recoil of the nucleus by means of the cloud chamber, by observing simultaneously the electron and the nuclear recoil. The idea of observing the event by introducing a gaseous radioactive material into a cloud chamber is an old one. The difficulty is that, if the cloud chamber is used in the ordinary way, the track due to the recoil nucleus is so short that it appears only as a point at the beginning of the electron track, indistinguishable from the droplets due to the electron. The nucleus does, however, produce a number of ion pairs in a small region of space, and the number is some function of the kinetic energy of the nucleus. If, in the absence of an electric clearing field, the expansion of the chamber is delayed about $\frac{1}{4}$- to $\frac{1}{2}$-second after the beta-disintegration, the cluster of ions will be found to be nicely spread out (by diffusion) into a spherical region several millimeters in diameter and the number of ions can be determined by counting the droplets. If a magnetic field is provided, the curvature of the electron track can be measured, and thus the simultaneous measurement of the electron and recoil momenta can be made. In practice, the electric clearing field is automatically switched off, say $\frac{1}{4}$-second before each expansion. Diffuse tracks of all ages up to $\frac{1}{4}$-second will then appear, and tracks of greater age will not appear because their ions will have been swept out.

Cl^{38}, in the form of ethylene dichloride was used as the gaseous radioactive material. The Cl^{38} disintegration is complex, about half going to the ground state of A^{38}, giving a 5-Mev beta-spectrum, and the other half going to an excited state, giving a 1.2-Mev beta-spectrum. In the recoil experiments the ambiguity was avoided by excluding all cases in which the electron had less than 1 Mev.

Figure 7 shows the number of droplets due to the nuclear recoil, and the momentum of the electron, each dot representing a disintegration. The relation between the number of droplets and the kinetic energy of the recoil presents a difficult problem. Since the recoil has such a small velocity, it is reasonable to suppose that it will dissipate a considerable part of its energy in heat and in molecular dissociation, rather than in ionization, so that the assumption of one ion pair for each 30-ev loss, as in the case of fast particles, may be too small.[32] On the other hand, it was shown very strikingly by Crane and Halpern,[33] in an auxiliary experiment, that molecular dissociation and activation cause droplet formation. A further possibility, namely that soft x-rays, ultraviolet quanta or Auger electrons may result from the readjustment of the electronic structure of the daughter nucleus after beta-decay seems to have been eliminated theoretically, by Hebb.[27] Lacking quantitative information on the whole question of the relation between droplets and energy, it was necessary to make an arbitrary adjustment in drawing the theoretical curves. The three curves in Fig. 7 represent (1) neutrino and electron escaping in the same direction, (2) opposite directions, and (3) no neutrino. All three curves come together at the upper right-hand corner of the diagram, so if there were enough experimental points in that neighborhood, the adjustment would not be arbitrary. Actually, the number of points was small, so there is considerable arbitrariness in the adjustment. It was necessary, also, to assume that the number of droplets was proportional to the energy of the recoil.

The conclusion to be drawn from the experiment is that momentum is not conserved in the system consisting of the electron and nucleus alone. The basis for such a conclusion is simply that the recoils associated with low energy elec-

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

[32] L. Wertenstein, Phys. Rev. **54**, 306 (1938).

[33] H. R. Crane and J. Halpern, Phys. Rev. **54**, 306 (1938).

trons have as much energy as those associated with high energy electrons. Another way of stating this is that the distribution of points shows no tendency toward a slope from lower left to upper right, as would be expected if there were no neutrino. The experiment is in principle able to give, in addition, the distribution in angle between electron and neutrino, but the errors so far are too great to permit one to say anything in that respect.

2. The time of flight method of measuring the velocity of recoil nuclei has very recently been introduced by Sherwin.[34] His apparatus is shown schematically in Fig. 8. The time of flight is measured between the P^{32} layer and the grid. This region is field free. The ions are then accelerated by a potential difference between the grid and the first electrode of the electron multiplier tube. The pulse from the Geiger counter triggers the horizontal sweep on an oscilloscope and the arrival of the recoil ion at the electron multiplier tube produces a vertical pip. The position of the pip along the horizontal axis gives the time of flight of the recoil ion. Counts were made with angles of 180°, 135°, 90°, and 45° between the directions of the electron and recoil ion, and the final data, of course, consisted of plots of the distribution in momentum of the recoils, one for each of the four different angles. The electron energies were not measured.

The demonstration that momentum is missing which may be assigned to the neutrino can be made in two ways. First, using the case of $\phi=135°$, 90°, and 45°, it is only necessary to show that recoil atoms are counted at all because in those cases the direction of the recoil is obviously not opposite to the electron direction. It must, of course, be established that the recoils observed at those angles are not accounted for by 180° recoils which are scattered at the substrate, but the intensities observed in the present experiment make such an explanation improbable. Second, if one uses the case of $\phi=180°$, a recoil momentum distribution calculated on the assumption of no neutrino can be compared with the actual distribution. The two distributions are strikingly different. The distributions for the four angles are shown in Fig. 9.

[34] C. W. Sherwin, Phys. Rev. **73**, 216 (1948).

The most important part of the experiment is the study of the neutrino-electron angular correlation. The angle of measurement (180°, 135°, etc.), the recoil momentum, and a knowledge of the upper limit of the beta-ray spectrum, constitute enough data for the computation of the angle between the neutrino and electron directions in each disintegration. The alternative method of treatment, which is the one used by Sherwin, is to compute the distributions expected on several different assumed correlation functions, for each angle of measurement, and to compare them with the experimental curves. The correlation functions tried were

(1) $$W(\theta)d\Omega=(3/16\pi)(1-\beta\cos\theta)^2 d\Omega,$$

(2) $$W(\theta)d\Omega=(1/4\pi)(1-\beta\cos\theta)d\Omega,$$

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

(scalar or pseudoscalar first forbidden)

(4) $$W(\theta)d\Omega=(1/4\pi)d\Omega,$$

where β is v/c for the electron, and p and q are the momenta of the electron and neutrino, respectively. These predict distributions for the 180° case which are increasingly peaked at the upper limit in the order given. The theoretical curve, $1-\beta\cos\theta$, is an excellent fit with the experimental 180° curve, as shown in Fig. 9, but the fit deteriorates as the angle decreases. The 180° curve should, as the author points out, be given more weight than the others because the recoils have the greatest energy and comparatively less distortion of the curve toward lower energies due to energy loss in the escape of the recoil from the surface would be expected. The question then is, how much more sharply peaked at the upper limit would the 180° curve be under conditions of no energy loss? While there are no apparent reasons for thinking that distortion is very large, as will be indicated in the next paragraphs, it is possible that the real 180° distribution is more strongly peaked than the $1-\beta\cos\theta$ curve.

The accuracy of the results rests almost entirely upon the problem of the escape of the recoil ions from the surface, so let us ask the usual set of questions. (1) Is the active material on the surface or in depth in the substrate? The high value of specific activity of P^{32} now obtainable by pile irradiation helped enormously in this respect because sufficient activity could be obtained by evaporating less than a monolayer of phosphorus onto the substrate. Comparison of runs in which different procedures in the evaporation process, and different substrates were used, and in which different intervals of time elapsed between evaporation and observation gives some clue as to whether or not there was a depth effect. Out of about 38 surfaces 15 gave few or no recoils and five or six others gave an excessive number of low velocity recoils, indicating absorption in the layer, but the remaining ones gave consistent shapes for the momentum distributions, so it is probably safe to assume that in the latter there was negligible absorption. (2) Is the probability that a recoil is ionized dependent upon its velocity of escape? There is as yet no really satisfactory answer to this question. The daughter atom, sulfur, is born as a positive ion. If the substrate is a clean metal whose work function is less than the first ionization potential of sulfur (10.3 volts) the conduction electrons will neutralize the atom. This was tried by Sherwin and shown to be true. Since no metal has a work function as high as 10.3 volts, he was obliged to use insulators, LiF, NaF, and SiO_2. In this the situation is different: whether or not the atom is neutralized will depend upon whether or not there is in the immediate neighborhood of the atom an electron which can be freed for less than 10.3 volts. It is likely that the probability of neutralization depends primarily upon the nature of the material with which the recoil atom is in contact at the instant of leaving rather than upon its velocity. Therefore, in spite of the fact that less than 10 percent of the atoms came off ionized, one does not incline toward the belief that the velocity dependence was serious. (3) Is the direction of motion of the recoil modified by the substrate? If the phosphorus is in a monolayer, the change in direction for those atoms whose initial impulse is directed away from the surface will be small and due only to the energy of adsorption of the atom to the substrate. A recoil whose initial impulse is into the surface can suffer a reversal of direction by a single elastic collision only with an atom of mass greater than its own. All the substrates used, LiF, NaF, and SiO_2, are safe in this respect. An experimental test was made in which recoils emerging at 45° were counted, and no modification of the shape of the recoil momentum distribution was found. Thus scattering does not seem to have been of serious consequence.

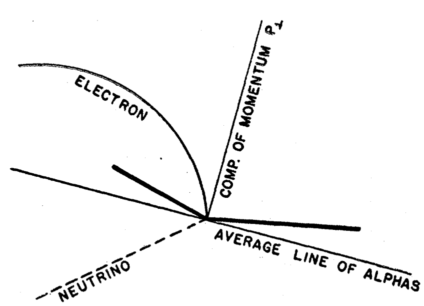

FIG. 10. The breakup of Li^8, showing the inequality of the ranges of the two alphas, and showing what is meant by the average line of the alphas and the perpendicular component of momentum.

In virtually all respects the method of Sherwin seems to yield the cleanest results that have yet been obtained on beta-ray emitters. In making this statement no comparison between Sherwin's experiment and Allen's is intended because the latter, which was also highly successful, gives information of a different kind.

The Break-Up of Li^8

An experiment that has been recognized for a long time as having intriguing possibilities is the observation of the disintegration of Li^8 in a cloud chamber. The reaction is

$$Li^8 \rightarrow Be^{8*} + e^- + \nu$$
$$\searrow He^4 + He^4.$$

The vector sum of the momenta of the final products may be assumed to be zero, because the Li^8 is initially at rest and the lifetime of the intermediate state, Be^8 is too short to permit any momentum transfer by collisions. The role played by the Be^8 is that its energy level determines the way in which the total available energy is divided between the beta- and the alpha-disintegrations. The Be^8 level[35–38] is extremely broad, but the maximum probability is for the alpha-pair to have about 3 Mev and the electron and neutrino together to have about 12 Mev. Fortunately the breadth of the Be^8 level does not introduce a corresponding uncertainty into the analysis of the momentum relations because in each disintegration the energy of the alpha-pair is measurable. The appearance that the disintegration of a Li^8 nucleus in the gas of the cloud chamber is expected to have is sketched in Fig. 10. The angle between the two alpha-tracks gives the component of recoil in the plane normal to the average line of the two alphas, and the inequality in ranges gives the component along the average line of the alphas. At the same time, the direction of emission and the momentum of the electron are measurable from its track when a magnetic field is applied to the cloud chamber. Thus, in principle, everything can be measured except the direction and momentum of the neutrino and they can be found by completing the momentum diagram. Such elegance has not yet been achieved, however, because of the rather severe technical difficulties of the experiment.

The first success has just been reported by Christy, Cohen, Fowler, Lauritsen, and Lauritsen.[39,40] In order to make the experiment feasible at all the authors had to use a set of conditions which fall somewhat short of the ideal ones outlined above, but photographs of the kind sketched in Fig. 10 were obtained, as well as valid statistical data bearing upon the neutrino hypothesis. A method was used in which the Li^8 was introduced into the cloud chamber on the surface of a very thin foil, so that in the disintegration one of the alpha-particles had to pass through the foil. The energy loss and scattering in the foil were small, and the technical advantages of this method over that of attempting to introduce the Li^8 directly into the gas were believed to compensate for the additional uncertainty in measurement occasioned by the presence of the foil. The Li^8 was made by bombarding lithium with 1-Mev deuterons from the electrostatic generator. A beryllium or gold foil which was coated with a very thin layer of LiOH was exposed to the beam, in vacuum, for about $\frac{1}{2}$-second. The foil, which then carried some of the short lived activity, was quickly moved to the center of the cloud chamber by an ingenious mechanical devise. The mechanism moved the foil from the vacuum of the accelerating tube, through a seal, through a rough pumping chamber, through a second seal into the cloud chamber, and back again, repeating the cycle automatically for each expansion of the chamber. The transfer into the chamber required 1.5 second (about two half-lives of Li^8).

Out of approximately 10,000 cloud-chamber photographs, 217 alpha-particle pairs were obtained which satisfied the criteria for measurement. Twenty-eight of these had electron tracks associated with them and could, therefore, be analyzed for "missing" momentum. It will be recalled that when the Be^8 breaks up, the average line of the two alphas (line of breakup) may have any direction with respect to the direction in which the Be^8 recoiled in the beta-neutrino emission. Therefore one component of the recoil momentum will be measurable through the slight deviation from 180° of the directions of the two alphas, and the other component will be measurable through their difference in range. The maximum possible values are about 6 degrees and 20 percent, respectively. The range difference is made difficult to measure in the present method by the fact that always one alpha has to pass through the foil and the LiOH layer, often obliquely. After investigation of the errors to be expected, the authors concluded that the range difference measurements could not be done with sufficient accuracy, largely because of energy loss in the LiOH layer. The expected mean error in the angle, on the other hand, was shown to be only about 25 percent; therefore only the component of momentum of the Be^8 perpendicular to the line of breakup and in the plane of the chamber was determined. It was possible, then, in the 28 cases in which the momentum of the

35 W. A. Fowler and C. C. Lauritsen, Phys. Rev. **51**, 1103 (1937).
36 L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, Phys. Rev. **51**, 1106 (1937); **54**, 657 (1938).
37 C. Smith and W. Y. Chang, Proc. Roy. Soc. **A166**, 415 (1938).
38 T. W. Bonner, J. E. Evans, C. W. Malich, and J. R. Risser, Phys. Rev. **72**, 163 (A) (1947); see also data on the Be^8 level contained in the paper of Christy, *et al.*
39 W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. **72**, 738 (A) (1947).
40 R. F. Christy, E. R. Cohen, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Phys. Rev. **72**, 698 (1947).

electron was known, to solve for the momentum to be assigned to the neutrino, but only in the component described. This was called $P_{\perp}$. The maximum value that $P_{\perp}$ could have (P_{max}) was calculated in each case using the measured energy of the electron and the upper limit of the beta-spectrum. In most of the disintegrations $P_{\perp}$ was somewhere between zero and P_{max}, meaning that momentum was "left over" to be assigned to a neutrino but of course the errors in the individual measurements were large. In the 189 events in which only the alpha-tracks were seen the component of momentum perpendicular to their average line and in the horizontal plane was measured. This was called $p_{\perp}$. The distribution, in that component, was compared with calculated distributions on the assumption of no neutrino and of a neutrino having random angular correlation with the electron direction. The data fit the latter assumption somewhat better than the former, but the difference is by no means striking. A more reliable statement of of the outcome is that $\langle(p_{\perp}/p_{max})^2\rangle_{Av}$ for all the 217 cases was 0.20 ± 0.02, which was slightly more than twice the value calculated on the assumption of no neutrino. When the momentum relations are worked with in only one component, the very considerable differences between the predictions of various theoretical assumptions "wash out" to a large degree. A great deal will be gained, therefore, when further technical progress makes possible the measurement of all three components of momentum.

2. An interesting technique for introducing Li^8 into the gas of a cloud chamber is at present being developed by Bonner[41] and his associates at the Rice Institute. A thin foil separates the vacuum of the deuteron accelerating tube from the cloud chamber. The lithium to be bombarded is deposited upon the cloud chamber side of the foil. The deuteron beam is fired through the foil and many of the Li^8 nuclei which are made have enough forward momentum so that they leave the foil and enter the cloud-chamber gas. An electric field is then applied inside the cloud chamber, perpendicular to the direction of the beam, so as to pull the Li^8's (most of them are positive ions) into another part of the chamber so as to reduce the effect of the concentrated fogging by the deuteron beam. The chamber is expanded and the photograph taken about $\frac{1}{2}$-second after the deuteron beam is turned off. Many photographs of the alpha-pairs have been obtained and their energy distribution has been reported,[38] but as yet the associated electron tracks have not been photographed successfully.

[41] T. W. Bonner, private communication.

THE ABSORPTION OF NEUTRINOS

Possible Ways in which Neutrinos May Interact with Matter

The absorption of neutrinos by matter has been searched for in a variety of ways and over a wide range of absorption coefficients. There is no doubt that the charge of the neutrino is zero, so if it were to produce ionization it would have to do so by means of a short-range force of some kind. The possession of a magnetic moment by the neutrino would give an interaction with electrons and would be observed through the production of secondary electrons. Because the force would be of a short-range type, the energy transfers would be expected to be comparatively large, even though infrequent.[42] If there is any other kind of interaction by which a neutrino can transfer energy to a free electron, it lies completely outside our present knowledge. Aside from collisions with electrons, some effects which neutrinos might produce upon matter are: (1) The inverse beta-decay process, which, to be more exact, is like the inverse of the K-capture process in that it is the simultaneous absorption of a neutrino and emission of an electron. The cross section calculated[43] for this is in the neighborhood of 10^{-44} cm^2. (2) Collision of a neutrino with a nucleus with transfer of linear momentum. There is the possibility that the cross section for this is larger than the neutrino-electron cross section because nuclear forces are involved. (3) Non-capture excitation of nuclei by neutrinos, with subsequent emission of gamma-rays or, in the case of uranium, fission. (4) Effects at cosmic-ray energies. Our present experiments are limited to the use of neutrinos of a few Mev which we obtain from beta-decay. Until an artificial source of Bev neutrinos appears on the horizon, there is only the slight hope that cosmic-

[42] H. A. Bethe, Proc. Camb. Phil. Soc. **31**, 108 (1935).
[43] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947), p. 121.

ray studies will yield something on such interesting possibilities as the production of mesons by neutrinos.

Absorption Experiments

1. That neutrinos are not absorbed by small thicknesses of matter was shown by the experiments of Ellis and Wooster[44] in 1927 and Meitner and Orthmann[45] in 1930. They enclosed a sample of RaE in a capsule of wall thickness just sufficient to stop the beta-rays, and measured the heat evolved. The heat measured was precisely equal to the energy of the beta-rays integrated over the spectrum. Thus the possibility of an ionization or other heat-producing absorption process in that thickness of material was eliminated.

2. In the middle range of absorption coefficients there is abundant evidence to show that neutrinos do not produce ionization effects with an absorption coefficient which is near enough to that of nuclear gamma-rays, so that they are likely to be concealed by gamma-ray effects. The example that is probably the cleanest is an experiment that was done for quite a different purpose: that of Wu,[46] on the internal and external bremsstrahlung of P^{32}. P^{32} emits no gamma-rays. Using a strong source, she measured the ionization in an ionization chamber, with only enough material interposed to stop the beta-rays. Assuming, as she did, that the radiation measured was x-rays, and subtracting that which was external bremsstrahlung due to the stopping of the electrons in the filter, her data show that only 0.004 quanta per disintegration electron came from the P^{32} source. That was equal to the calculated[47] intensity of internal bremsstrahlung to within the experimental uncertainty. From this experiment it is clear that if neutrinos are absorbed in an ionizing process, the mass absorption coefficient does not lie between the limits of, roughly, 10 and 0.001 g^{-1} cm^{-2}.

3. The range of absorption coefficients or absorption cross sections beginning about where those of gamma-rays end, and extending down to much smaller values has been covered by the experiments of Chadwick and Lea,[48] and Nahmias.[49] Chadwick and Lea shielded a 5-mc RaE source with lead up to 5.8 cm thick, and measured the residual ionizing radiation with a pressure ionization chamber. Their conclusion was that neutrinos do not produce more than one ion pair per 150 kilometers of path in air, N.T.P. Nahmias carried out the same kind of experiment on a more ambitious scale, using 5 grams of radium and shielding with lead up to 91 cm in thickness. He was able to place the upper limit at one primary encounter in 300,000 kilometers of path in air. His computation of the frequency of primary encounters was done with the use of Bethe's formula[42] for the energy distribution of the electron secondaries produced by the neutrinos. If we wish to find the average number of ion pairs expected per primary encounter we have to refer to Bethe's formula and work backwards from the result that Nahmias gives. We find that an upper limit of, roughly, one ion pair per 3000 kilometers of air path is indicated.

4. The flux of neutrinos just outside a chain-reacting pile is far greater than that from any terrestrial source heretofore available. The gamma-ray and neutron intensity is very close to zero due to the heavy shielding around the pile. Wollan[50] has recently reported on a search for ionization effects of neutrinos in hydrogen, using the pile as a source. The fact that the proton is a nuclear particle made it seem worth while to look for this interaction, in spite of the fact that a cross section of the required size has been shown not to exist for neutrino-electron collisions. Because of the small mass of the proton, a collision of a high energy neutrino with a proton should give the latter only enough kinetic energy to produce one or more ions in the gas. Wollan's results were negative and gave an upper limit of 2×10^{-30} sq. cm for the cross section for collision.

5. The use of the large neutrino flux from a chain-reacting pile to test for the inverse beta-decay process has been a subject of conversation among physicists since the advent of the pile, and it would be surprising if experiments of this

[44] Ellis and Wooster, Proc. Roy. Soc. **A117**, 109 (1927).
[45] Meitner and Orthmann, Zeits. f. Physik **60**, 143 (1930).
[46] Chien-Shiung Wu, Phys. Rev. **59**, 481 (1941).
[47] J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936).
[48] J. Chadwick and D. E. Lea, Proc. Camb. Phil. Soc. **30**, 59 (1934).
[49] M. E. Nahmias, Proc. Camb. Phil. Soc. **31**, 99 (1935).
[50] E. O. Wollan, Phys. Rev. **72**, 445 (1947).

sort were not going forward at the present time in one or more of the government laboratories. An experiment on the inverse beta-process, using a comparatively minute neutrino source, was made by the author[51] in 1939. The reaction

$$Cl^{35}+\nu+1.3\text{ Mev}\rightarrow S^{35}+e^{-};$$
$$S^{35}\rightarrow Cl^{35}+e^{+}+\nu+0.3\text{ Mev}$$

was chosen because of the small energy threshold and because of the ease of isolating the product, S^{35}. The neutrinos were obtained from a 1-mc mesothorium sample which was in equilibrium with its products. In the computations only the neutrinos having greater than the threshold energy were considered. The source was placed at the center of a 3-pound bag of NaCl and left for 90 days. The salt was then dissolved and the sulfur was extracted. No beta-activity was found in the sulfur. The sensitivity of the experiment was such that a cross section of 10^{-30} cm^2 for the inverse beta-process could have been detected.

Large Scale Effects of the Absorption of Neutrinos

According to the Bethe cycle[52] for the production of energy in the sun, about six percent of the energy is being poured forth in the form of neutrinos. About the same figure can be obtained also from more general considerations. We can assume that in any system of reactions leading directly or indirectly to the synthesis of elements out of hydrogen one beta-decay will result from every two protons used up, because the final nuclei will contain about half protons and half neutrons. The average energy of the neutrinos may be taken as 1 Mev. Each proton used up will, on the other hand, release 6 to 8 Mev. These figures lead to a value which checks very well with that obtained from the Bethe cycle. If the average cross section for absorption of the sun's neutrinos in solar or earth material were to lie in a favorable range (the order 10^{-34} sq. cm per atom) some interesting large scale effects would be observable. For example, if the range or mean free path of the neutrinos in the sun were of the same order of magnitude as the radius, they would serve as a means by which energy produced at the center could be transported immediately to a great distance from the center, and would have an effect upon the internal temperature gradient. Another example is the heat delivered to the interior of the earth. The effect would be a maximum if the absorption cross section were of the order 10^{-35} cm^2, assuming that the neutrinos originate at the center of the sun. On the further assumption that the absorption cross section does not depend upon the neutrino energy or the kind of absorbing material, it is easily shown that the rate of heat absorption in the earth would be between 10 and 100 times the rate at which heat is known to be flowing outward through the earth's surface.[53] This, therefore, excludes 10^{-35} as a possible cross section. The assumption made above, namely that the cross section is not sensitive to energy or kind of absorber, is not an unreasonable one if it is assumed that an ionization process is responsible for the absorption. But if an absorption mechanism which is sensitive to energy and material, such as the inverse beta-process, is introduced into the calculation, the result is modified considerably. It may be noted that the energy spectrum of the neutrinos produced in the Bethe cycle is not unfavorable for the inverse beta-process. Half the neutrinos come from O^{15}, whose upper limit is 1.7 Mev. Thus all isotopes whose beta-spectra have upper limits less than 0.7 Mev are eligible for production by the absorption of neutrinos from O^{15}. The other half of the neutrinos, which come from N^{13} (upper limit 1.2 Mev) are of little importance.

It will be remembered that Nahmias, in his attempt to detect absorption effects leading to ionization, placed the upper limit at one primary encounter in 300,000 kilometers of air, which is a cross section of the order 10^{-30} sq. cm per atom. In view of the present theory of energy production in the sun, we might add the following as a footnote to his work. A cross section of 10^{-30} cm^2, which represents his limit of detection, is too large to allow the escape of neutrinos from the sun, and therefore he was correct in assuming that his 5 grams of radium at 1 meter was his principal source of neutrinos. However, if we consider the situation for a cross section of 10^{-34} cm^2, we find that the neutrino flux through his Geiger counters would have been 10^5 times that from his radium and his expected counting rate would have been ten times background. Thus

[51] H. R. Crane, Phys. Rev. **55**, 501 (1939).
[52] H. A. Bethe, Phys. Rev. **55**, 434 (1939).
[53] A. E. Benfield, Am. J. Sci. **425**, 1 (1947).

a cross section of 10^{-29} cm^2 gives the same counting rate as 10^{-34}, and 10^{-30} gives the same rate as 10^{-35}. 10^{-34} and 10^{-35} are excluded, as already shown, on geophysical grounds. The same type argument, applied to the author's experiment on the inverse beta-process, eliminates the possibility of a cross section of the order 10^{-35} cm^2 for that mechanism.

By combining the results of the absorption experiments with the geophysical observations it can be concluded that all cross sections greater than 10^{-36} (or possibly 10^{-37}) cm^2 for both the inverse beta-decay and ionization processes are excluded, with the possible exception of one small region in the neighborhood of 10^{-31} to 10^{-32} cm^2. This cross section lies just beyond the range of the experiments on absorption so far reported using terrestrial sources, and yet is large enough to prevent the escape of neutrinos from the sun. But this gap in the data will certainly be closed within a short time by experiments using the chain-reacting pile as a neutrino source.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER EXPERIMENTS

The energy relations in the beta-decay, namely, the fact that the disintegrating nucleus loses an amount of energy corresponding to the upper limits of the beta-ray spectrum and that the particles emitted are ordinary electrons, have been well established experimentally. The mass of the neutrino has been shown from energy balance equations to be smaller than that of the electrons if not zero. The opportunity for making more sensitive measurements of the mass, particularly in cases in which the energies of the beta-spectra are small, still exists. A further experiment which would be of interest would be a comparison of the apparent rest mass of the neutrino as given by energy balances involving very high energy beta-spectra, B^{12} for example, with that obtained from the very low energy spectra. The energy balance for B^{12} was investigated in 1936 by Fowler, Delsasso, and Lauritsen,[54] but the data available at that time were not very accurate. If the apparent rest mass were found to be greater in the first than in the second case it would suggest either that the end point of the spectrum was not correctly given by the present theory or by inspection, or that the rest mass could not be assumed to be unique. The former would be the first to be considered, of course, and one is reminded that not so long ago the method of extrapolation used (the K.U.) did give an error which was proportional to the energy of the end point.

It seems now to have been adequately shown experimentally that there is apparent non-conservation of momentum in the beta-decay, and that, quantitatively, the maximum amount of extra momentum found is in satisfactory agreement with that called for either by the neutrino hypothesis, or by much more general theoretical arguments which relate the disappearance of momentum to the disappearance of energy. In view of this it seems reasonable to say that further experiments which contain only the possibility of demonstrating the apparent non-conservation of momentum will not be of much value. The principal field to be exploited now by means of the recoil experiments is the determination of the neutrino-electron angular correlation functions. The work to be done is extensive, because different correlation functions are given not only by different variations of the beta-ray theory but by the different degrees of forbiddenness of the beta-transition. Sherwin's experiments mark a notable advance in this direction. While his results cannot yet justify selecting one correlation function as being the right one, they have perhaps reached the point where the number of possibilities may be reduced considerably.

Another line of work that still has important information to give forth is the continued development of the technique introduced by Allen on the measurement of the recoil in K-capture to the point where it can be decided conclusively whether or not the recoil atoms are monoenergetic. This, as I have pointed out, is the one experiment feasible at the present time which can justify the hypothesis that all the missing energy in the beta-disintegration is taken away by a single neutrino. Needless to say one would give high odds against an answer in the negative; nevertheless, a key experiment such as this should be done as a matter of policy. Work with a K-capture isotope in gaseous form would have certain obvious advantages if one were trying to prove that the recoils were monoenergetic.

[54] W. A. Fowler, L. A. Delsasso, and C. C. Lauritsen, Phys. Rev. **49**, 561 (1936).