method of King and are, therefore, not really qualified to criticize it. We do know, however, that his values of the moments of inertia do not yield lines at positions which fit our data as well as the values of the moments of inertia which we have given in Table V. We believe this to be because his values are chosen so as to give the best agreement at considerable distances from the center of the band where the centrifugal distortion is of considerable significance. They must, therefore, deviate from the values which would give the best fit near the center of the band. In our determination, compensation for centrifugal stretching has also been neglected. The values of the moments of inertia were, however, determined from term values of small J value where the centrifugal stretching is small and may be neglected. Since the lines which have been used to determine these term values are known accurately to about 0.05 cm^{-1}, we believe the values obtained by us for the moments of inertia are somewhat more reliable.

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The Conservation of Momentum in the Beta-Decay of Y^{90}*

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Monolayer sources of yttrium (90) are formed by evaporation in a vacuum of 10^{-7} mm of Hg. The momentum of individual recoil ions is measured by timing their flight in a field free space. The positively charged Zr (90) recoils appear to lose about 6-electron volts energy as they escape from the surface. If a 6-electron volt correction is made to the observed recoil spectra, there is good agreement regarding shape and absolute amplitude with those recoil spectra calculated on the assumption of a neutrino-electron angular correlation function of $(1-\beta\cos\theta)^2$. For this function the most probable angle between the neutrino and the electron is $\sim 135°$. These results are in agreement, within experimental error, with earlier data obtained with P^{32}. The exact limits of error due to chemical effects at the surface cannot yet be assigned, so it is not possible to make a definite selection of the form of the neutrino-electron angular correlation function.

1. INTRODUCTION

In earlier experiments[1] the momentum spectra of the recoil ions from monolayer sources of P^{32} ($E_{max}=1.72$ Mev, half-life, 14.3d) were measured. It was concluded that momentum is not conserved between the electron and the recoil nucleus. If one assumes the existence of a neutrino, which is most probably emitted in the opposite hemisphere from the electron, one accounts for the experimentally observed recoil momentum spectra. The experiments reported here measure the recoil momentum spectra of yttrium (90) ($E_{max}=2.16$ Mev, half-life, 62 hr.).

These experiments permit a rather critical test of the previous results, since the Zr^{90} recoil ion from Y^{90} is very different from the S^{32} recoil ion from P^{32}. The recoil ions in these two cases differ appreciably regarding (1) maximum velocity, (2) maximum energy, (3) maximum momentum, (4) mass, (5) ionization potential (S = 10.3 volts, Zr = 6.92 volts), and (6) the fraction of the recoils that escape in the charged state. If one assumes a $(1-\beta\cos\theta)^2$ neutrino-electron angular correlation function for both cases, about 8 percent of the sulfur, and about 87 percent of the zirconium recoils escape charged.

In addition, the nature of the freshly evaporated foundation surface on which the monolayer is deposited is different. P^{32} was deposited on

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

quartz, NaF, and LiF. Y^{90} was deposited on quartz and tungsten. In all these cases, except for a 6-electron volt energy loss of the Zr ions, the recoil spectra are quite similar.

Only by varying the conditions at the surface over the widest possible range can estimates of the errors caused by surface effects be made. Changing the type of beta-active material as well as the type of foundation surface provides a method of distinguishing between nuclear effects and chemical effects.

2. THE EXPERIMENTAL METHOD

The apparatus is substantially the same as in the earlier experiments.[1] The velocity of the ionized recoil nucleus is measured by timing its flight over a field free path of 7.6 cm. The nucleus is accelerated (to 3000 volts) between two parallel grids, and then detected by an

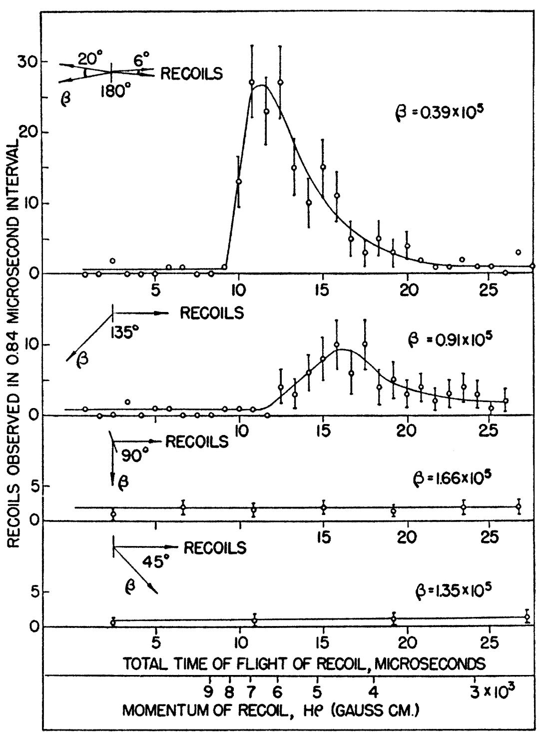

FIG. 1. *Observed time of flight distributions for the recoil ions from* Y^{90}. The yttrium, probably in the form of YO, is deposited on a freshly evaporated surface of tungsten. The angular apertures, for the detection of the beta-particles and the recoils, are the same for all four angles. The number equated to β is the total number of beta-particles detected by the Geiger counter during the collection of the recoil data. The failure to observe recoils, above background, at 90° and 45° is consistent with the neutrino hypothesis.

electron multiplier. This latter process takes a calculated time of 0.42 microsecond, which is essentially constant for all the recoil ions. The beta-particles are detected at 180°, 135°, 90°, and 45° with respect to the direction of the recoil ions. The beta-particles are detected in a 10 degree half-angle cone and the recoils in a 3 degree half-angle cone for all four directions.

The Y^{90} is separated from the parent Sr^{90} (obtained from the Clinton Laboratories) by the method of J. D. Kurbatov and M. N. Kurbatov.[2] In this method, with the two radioactive materials in a pH 9 solution, most of the Y^{90} is absorbed on a filter paper while the Sr^{90} filters through the paper. Only about 1 percent of the activity of the final, carrier free, Y^{90} solution is due to Sr^{90}. The specific activity of this final solution (0.1 N HCl) is estimated to be less than one milligram of non-volatile matter per millicurie of Y^{90}.

The Y^{90} is evaporated (at about 2000°C) from a clean 10-mil tungsten wire bent in the form of a small hairpin. The catching surface, made of mica or thin glass, has a thickness ranging from 1.8 to 0.5 mg/cm^2. When quartz is used, the mica (or glass) is first coated with a thin gold surface to reduce the effect of electrostatic charges due to the escape of the excess number of beta-particles over the number of charged recoils. Recently it has been shown by Robley C. Williams[3] that polished or fire glazed glass surfaces have irregularities of the order of 5 angstroms. Thus, even when approaching the atomic scale, the blown glass films used in some of the experiments with Y^{90} are not very rough.

The catching surface, freshly coated with a few atomic layers of tungsten or quartz, is exposed to the evaporating Y^{90} for about 15 or 20 seconds when the 10-mil filament is at the most favorable temperature. In determining this temperature, it was observed in an auxiliary system that 90 percent of the Y^{90} activity evaporated from the 10-mil tungsten wire in about 60 seconds when the current was increased from 4.5 amperes to 4.8 amperes. Up to the 4.5-ampere point practically none of the Y^{90} evaporated. Even with the aid of this calibration,

[2] J. D. Kurbatov and M. N. Kurbatov, J. Phys. Chem. 46, 441 (1942).
[3] R. C. Williams (to be published).

only five out of sixteen surfaces showed the characteristic time of flight distributions which are interpreted as being due to monolayer surfaces. Figure 1 shows an example of these data, for which the best statistics were obtained. The eleven "bad" or "thick" surfaces showed a large number of low momentum recoils, and were in all respects identical to the "good" surfaces after they were five or six hours old. The "good" surfaces required anywhere from 20 to 100 minutes to begin to show signs of contamination. Both quartz and tungsten foundation surfaces gave the same time of flight distributions.

Studies with the mass spectrograph[4] have shown that yttrium evaporates from a tungsten surface as positively charged YO ions. Therefore, in these experiments, the yttrium is probably deposited on the catching surface as YO. This means that the recoil ion Zr^+, must break a bond with an oxygen atom in order to escape from the monolayer surface as a free ion. It is shown later that there is definite evidence of loss of about 6-electron volts energy by the recoil Zr^+ ion as it escapes the surface. The breaking of the oxygen bond may be the principle cause of this energy loss. This "work function" effect did not appear to be present in the P^{32} experiments, although it could have been obscured by the larger experimental error (due principally to the shorter time of flight).

To be certain that the recoil ions observed in Fig. 1 are really mass 90, their mass was measured by the same method used in the P^{32} experiments. A fine mesh, grounded grid was placed 3 millimeters in front of the monolayer surface. The surface was then placed successively at 0, 50, 100, 160, and 235 volts negative with respect to ground, thus adding different amounts of energy to the initial energy of the recoil ions. Time of flight spectra were observed at each of these voltages. The minimum time of flight was observed for each spectra, and from this time the maximum velocity of the recoil ions was calculated. These measured velocities all agree very well with an initial maximum energy of about 36 electron volts, and a mass of 90 ± 5. The possibility that the recoil ion is mass 106 (ZrO^+) is definitely ruled out. A careful examination of these results also sets the limit of the zero error in the time of flight measurements at 0.1 microsecond.

[4] R. J. Hayden, private communication.

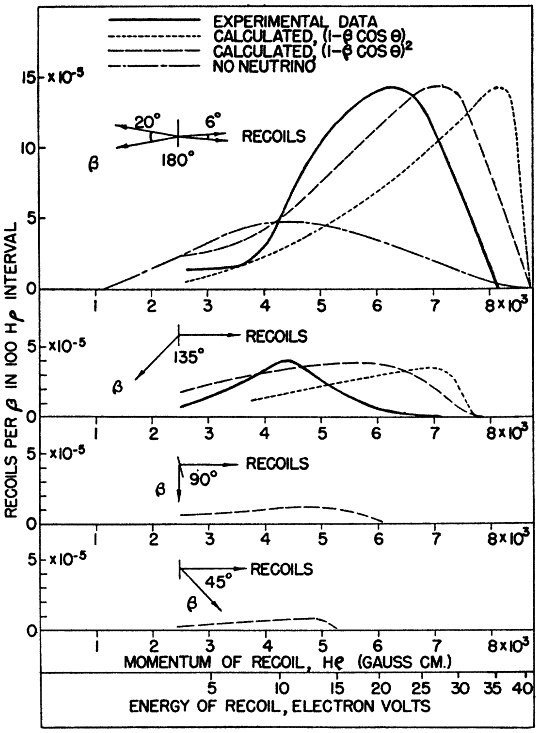

FIG. 2. *Comparison of observed recoil momentum spectra with those calculated from the neutrino hypothesis.* The 6-electron volt displacement of the observed spectra with respect to the calculated spectra is assumed to be due to the binding energy of the Zr^+ recoil ion to the surface. The calculated spectra for the $(1-\beta\cos\theta)^2$ and the $(1-\beta\cos\theta)$ neutrino-electron angular correlation functions were multiplied by 0.87 and 0.56, respectively, before plotting. This normalizes the amplitudes of the calculated 180° curves to the amplitude of the curve observed at 180°. The "no neutrino" calculated curve, which is just the spectrum of the detected electrons, is multiplied by 1/50 before plotting. The 90° and 45° calculated spectra for both the $(1-\beta\cos\theta)^2$ and the $(1-\beta\cos\theta)$ cases are nearly indistinguishable on the scale of the figure, so only one case is plotted.

3. INTERPRETATION OF THE DATA, AND COMPARISON WITH THEORY

The time of flight diagrams in Fig. 1 are plotted as momentum spectra in Fig. 2. Also plotted in Fig. 2 are the momentum spectra calculated on the following three assumptions:

(a) There is no neutrino. Recoils should appear only for the 180° case. These recoils should have the same shape spectrum as the electrons detected by the Geiger counter, and they should have a very high intensity. In fact, one should observe a recoil for every tenth beta-particle detected. In plotting the calculated recoil spectrum for this case, it was necessary to first multiply all the ordinates by 1/50. It has been assumed here, and in the following cases, that the original beta-particle spectrum for Y^{90} is that given by the Fermi theory for an allowed transition. That this is not an improbable assumption is shown by the cloud-chamber measurements by Stewart, Lawson, and Cork.[5] The end point is taken to be 2.16 Mev, or 8730-gauss cm. This predicts a maximum recoil energy of 40.7 electron volts for mass 90 recoil atoms. The spectrum as plotted in the 180° curve in Fig. 2 is corrected for the 15 mg/cm^2 total absorber between the monolayer source and the Geiger tube.

(b) A neutrino is assumed to exist whose probability of entering a solid angle element $d\Omega$, which makes an angle θ with respect to the direction of the electron, is $3/16\pi(1-\beta\cos\theta)^2 d\Omega$. For this function, the most probable angle between the electron and the neutrino is about 135°. This can be called a "backward" neutrino as contrasted to a "forward" neutrino such as is predicted by a $(1+\beta\cos\theta)$ function.

(c) A neutrino is assumed to exist whose probability of entering a solid angle element $d\Omega$, which makes an angle θ with respect to the direction of the electron, is $1/4\pi(1-\beta\cos\theta)d\Omega$. For this function, the most probable angle between the electron and the neutrino is about 120°. This function is predicted by both the scalar and pseudoscalar forms of the Fermi theory for an allowed transition.

β is the ratio of the velocity of the electron to the velocity of light.

The neutrino is assumed to share the total energy of 2.16 Mev with the electron, to have a mass small compared to the mass of the electron, and to have a momentum of E_ν/c. The electron multiplier is assumed to have 100 percent efficiency for 3000 volt ions.

Before plotting the calculated momentum spectra, for the $(1-\beta\cos\theta)^2$ case in Fig. 2, all the ordinates were multiplied by 0.87, which normalizes the amplitude of the 180° curve to the observed one. This means that about 87 percent of the recoil ions escape charged if this angular correlation function is correct. However, since the exact solid angle subtended by the "sensitive" area of the electron multiplier and the multiplier efficiency are not precisely known, the fraction of recoils escaping charged could be anywhere from 50 to 100 percent. A significant point here is the comparison of the 87 percent figure with the corresponding figure of 3 to 8 percent for the sulfur recoils from P^{32} (for the same neutrino-electron correlation function). In other words, per beta-particle, one observes about 10 times as many recoils from Y^{90} as from P^{32}.

In the $(1-\beta\cos\theta)$ case, all the calculated curves were normalized to the 180° observed curve by the factor 0.56.

Other recoil momentum spectra calculated on the basis of more "forward" neutrinos are plotted in the earlier paper. Since both the Y^{90} and P^{32} electrons are assumed to have about the same shape spectra, with E_{max} considerably in excess of mc^2, the recoil momenta spectra will have similar shapes. The very sharp high momentum peaks in the 180° curves predicted by both the "random" and also the "forward" neutrinos were never observed for either P^{32} or Y^{90}.

The most noticeable discrepancy between the observed and calculated recoil spectra is that the observed spectra (for both 180° and 135°) fall short of the maximum theoretical energy by about 6 electron volts. This is a real effect, and is definitely outside experimental error estimated to be ± 3-electron volts in this part of the spectrum. A possible explanation of this energy loss is the binding energy of the Zr^+ ions to the surface and to the oxygen atom to which they are probably attached. The abnormally low number of recoils below about 10-electron volts energy for both the 180° and 135° cases substantiates this explanation. If all of the ions whose initial energy was less than 6 electron volts failed to escape the surface, the whole low momentum region of the observed recoil spectrum would be lowered in intensity.

The second discrepancy between the observed and calculated recoil spectra is the failure to observe any recoils above background for the 90° and 45° cases. This is expected on the neu-

[5] D. W. Stewart, J. L. Lawson, and J. M. Cork, Phys. Rev. **52**, 901 (1937).

trino hypothesis, since the predicted amplitude of these recoil momentum spectra is only about twice the random background. The statistics are not good enough to permit the detection of this small an effect. Also, a 6-electron volt energy loss would strongly attenuate these spectra, making their detection still more difficult. This situation is considerably different from the P^{32} case where too many low energy recoils were observed at both 90° and 45°.

It is evident from Fig. 2, if a 6-electron volt binding energy correction is made, that a $(1-\beta\cos\theta)^2$ neutrino-electron angular correlation function accounts in an almost quantitative manner for the observed spectra. The $(1-\beta\cos\theta)$ function cannot definitely be ruled out. However, the "random" neutrino, the "forward" neutrino, and "no neutrino" predict curves of very different shape (see Fig. 5 in earlier paper), and of very different amplitudes (factors of 5 to 50), compared to observations. It does not seem possible to reconcile these cases with the observations.

The conclusion, that $(1-\beta\cos\theta)^2$ gives an adequate explanation of the observations, is in agreement with the data of P^{32}. The earlier paper pointed out that in many respects the observed P^{32} data fitted the $(1-\beta\cos\theta)^2$ function as well as the slightly favored $(1-\beta\cos\theta)$ function.

These results are in disagreement with the very tentative conclusions which Jacobsen[6] drew from his measurements on the recoil energy spectrum of Kr^{88} (2.4 Mev, 2.7 hrs.). In this experiment there were some correction factors, whose direction was known, but whose magnitude was uncertain. A careful examination of Figs. 11 and 13 in Jacobsen's paper, suggests that, if the corrections are not too large, his data can be reconciled to the conclusion reached here.

The conclusion that a "backward" neutrino is adequate to explain the observations on both Y^{90} and P^{32} is probably in disagreement with the Fermi beta-decay theory,[7] since neither of these two nuclei would ordinarily be considered as "allowed" cases. In particular, the function $(1-\beta\cos\theta)^2$ is not even a possibility in the present formulation of the theory.

4. CONCLUSIONS

It is assumed that a 6-electron volt binding energy correction can be made to the Y^{90} data.

(a) The "no neutrino," "forward" neutrino, and "backward" neutrino assumptions all predict recoil momentum spectra whose shapes are in strong disagreement with the observations, and whose amplitudes are in disagreement with observations by factors of 5 to 50.

(b) If a $(1-\beta\cos\theta)^2$ neutrino-electron correlation is assumed, the shape of the predicted spectra agree rather well with the shape of the observed spectra. Furthermore, the absolute amplitudes (assuming 100 percent of the recoils escape charged) of both the 180° and 135° calculated spectra agree to within about 20 percent with the amplitudes of the observed spectra. The failure to observe recoils above the background at 90° and 45° is consistent with this neutrino assumption (as well as with the others mentioned above).

(c) The Y^{90} data is in agreement, within estimated experimental error, with the earlier data from P^{32}, except in absolute intensity. Only about 8 percent of the high ionization potential recoil ions from P^{32} appear to escape charged.

(d) No exact limits of error due to chemical effects at the surface can be set at the present time. The reproducibility of the recoil spectra for different chemical combinations at the surface, and the systematic disappearance of high momentum recoils at 135°, 90°, and 45°, suggest that the surface effects do not seriously interfere with their behavior as predicted by the neutrino hypothesis. These qualitative arguments must be replaced by exact measurements of surface effects before a final selection of the neutrino-electron correlation function is possible.

5. ACKNOWLEDGMENTS

The author is particularly indebted to Professor R. B. Duffield for pointing out the possibility of using Y^{90} for this experiment, and to Mr. Louis M. Smith for preparing several carrier free samples of Y^{90}.

[6] J. C. Jacobsen and O. Kofoed-Hansen, Mat. Fys. Medd. **23**, No. 12 (1945).
[7] D. R. Hamilton, Phys. Rev. **71**, 456 (1947).