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Determination of the Beta-Decay Interaction from Electron-Neutrino Angular Correlation Measurements*

J. S. ALLEN, R. L. BURMAN, W. B. HERRMANNSFELDT,† AND P. STÄHELIN,‡ *University of Illinois, Urbana, Illinois*

AND

T. H. BRAID, *Argonne National Laboratory, Lemont, Illinois*

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The angular correlation coefficients in the allowed beta decays of He^6, Ne^{19}, Ne^{23}, and A^{35} have been experimentally determined from measurements of the energy spectra of the recoil ions. The form of the beta-decay interaction has been deduced from these measurements. The experimental results are summarized in the following table together with the beta-decay interaction forms which are indicated by each measurement.

Isotope	Selection rules	Correlation coefficient	Interaction forms
He^6	G-T	-0.39 ± 0.05	*A*
Ne^{19}	F and G-T	0.00 ± 0.08	*ST* or *VA*
Ne^{23}	G-T	-0.37 ± 0.04	*A*
A^{35}	Mostly F	$+0.97\pm0.14$	*VT* or *VA*

It is apparent from the last column that the experimental results are consistent if we assume that the dominant beta-decay interaction is the *VA* combination.

INTRODUCTION

THE experimental determination of the specific form of the interactions responsible for nuclear beta decay has remained a critical problem ever since the original formulation of the theory by Fermi.[1] Bloch and Møller[2] probably were the first to point out that measurements of the electron-neutrino angular correlation in nuclear beta decay could be used to indicate the correct type of light-particle interaction in the Fermi theory. According to present theory, five independent relativistically invariant expressions can be chosen for the interaction Hamiltonian. These are usually called the scalar, vector, tensor, axial-vector, and pseudoscalar interactions and are denoted, respectively, by *S*, *V*, *T*, *A*, and *P*. The pseudoscalar interaction is negligibly small in allowed transitions and will be omitted in this study.

During the past ten years we have been conducting a series of electron-neutrino angular correlation experiments in an attempt to improve the accuracy of our methods to a degree which would permit an unambiguous determination of the beta-decay interactions. In general, these experiments have tended towards a procedure which requires only a direct measurement of the shape of the energy spectrum of the recoiling nuclei. A number of measurements of the electron-neutrino angular correlation have been made in the past by methods which involve the detection of the beta particle and the recoiling nucleus in coincidence.[3] The primary difficulty with all of the coincidence experiments is that the ratio of the true to chance coincidence counting rates decreases with increasing single counting rates. The statistical accuracy of most of our earlier experiments was limited by the chance coincidence rates so that further increases in counting rates were not advisable. The experiments to be described in what follows involve only the measurement of the energy of the recoil ion and thus require only one detector so that there is no limitation on the amount of activity which can be effectively utilized.

In this paper we report measurements of the energy spectra of the nuclear recoils from which the angular correlation factor may be deduced. We have made measurements on the positron emitters, A^{35} and Ne^{19}, and on the negatron emitters, He^6 and Ne^{23}. The results of these measurements give both the Fermi (F) and the Gamow-Teller (G-T) interactions and are consistent within themselves without requiring the results of other angular correlation experiments. Brief reports of the results have already been published.[4–6] In general, the real effect in these experiments has been about one-tenth the background at the peak of each recoil spectrum. In order to compensate for this unfavorable ratio very large numbers of counts have been accumulated at every datum point, either by continuing individual experiments for about one month while operating at the University of Illinois Cyclotron,

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† Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

‡ Now at the Swiss Institute of Technology, Zurich, Switzerland.

[1] E. Fermi, Z. Physik **88**, 161 (1934).

[2] F. Bloch and C. Møller, Nature **136**, 912 (1935).

[3] J. S. Allen, *The Neutrino* (Princeton University Press, Princeton, New Jersey, 1958), Chap. 5.

[4] Herrmannsfeldt, Maxson, Stähelin, and Allen, Phys. Rev. **107**, 641 (1957).

[5] Herrmannsfeldt, Burman, Stähelin, Allen, and Braid, Phys. Rev. Letters **1**, 61 (1958).

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or by using the very high activities available from the CP-5 Reactor at Argonne National Laboratory. In addition efforts have been made to improve the efficiency of collection of data.

Until recently our ideas concerning the nature of the beta-decay interaction has been largely based on the results of the experiment of Rustad and Ruby.[7] These authors measured the electron-neutrino angular correlation in the decay of He^6 and their results indicated that the tensor invariant is the dominant G-T interaction form. A more recent cloud chamber experiment by Csikai and Szalay[8] also favored the T interaction for He^6. During the course of our experiments several events occurred which suggested that a repetition of the He^6 neutrino recoil experiments would be highly advisable. First, our A^{35} experiment[4] yielded the unexpected result that the dominant Fermi interaction was V rather than S as had been deduced from combining the above-mentioned He^6 results with the neutron experiment of Robson[9] and the Ne^{19} experiments.[10–12] When the A^{35} results are combined with the neutron and Ne^{19} experiments, the indicated interaction combination is VA rather than the ST combination required when the He^6 results are considered. This apparent inconsistency has finally been eliminated by new experiments.

A second cause for repeating the He^6 experiment is the experiment by Goldhaber *et al.*[13] who measured the helicity of the neutrino in a G-T beta decay and found it to be negative (left-handed neutrinos). When supplemented by measurements[14] of the directional asymmetry of the beta decay of oriented nuclei or by measurements[15,16] of the electron polarization, this experiment indicates that the Gamow-Teller interaction is A. Another reason for repeating the He^6 experiment was supplied by the authors of the above-mentioned experiment on He^6, Rustad and Ruby, who, in a post-deadline paper at the 1958 New York meetings of the American Physical Society, expressed the opinion that certain experimental uncertainties make questionable the interpretations originally made from their results. Because the original apparatus had been destroyed it was not possible for them to make sufficiently accurate corrections to their data to make a meaningful interpretation. However, the trend of the corrections was in the direction of a negative correlation coefficient which would favor axial-vector in agreement with the above arguments.

Additional information favoring the VA combination has been supplied by several recent experiments. Lauterjung *et al.*[17] find that A is dominant in the decay of Li^8 which obeys Gamow-Teller rules. Burgy *et al.*[18] have measured the asymmetries in the beta decay of polarized neutrons. The results of this experiment appear to require VA. Pleasonton *et al.*[19] have also repeated the He^6 recoil experiment and are in agreement with the axial-vector conclusion. Barnes *et al.*[20] have made an independent measurement of the G-T interaction with Li^8 and are in agreement with A with an upper limit of 10% T.

The only experiment of fairly recent origin which is not in agreement with pure VA is the Ne^{23} work of Ridley.[21] The results of this experiment indicate a nearly even mixture of A and T for the G-T interactions. There is a small possibility that the assignment of G-T rules to both branches of the Ne^{23} decay scheme may be in error. However, if one assumes that the VA combination is indeed correct this information can be used to check the spin assignments for an isotope such as Ne^{23}. As has already been stated, our repetition of the Ne^{23} experiment is in agreement with other evidence for VA and indicates that the original assignment of pure G-T rules is correct.

Happily, recent theoretical investigations have also favored the VA interaction combination. Theories proposed independently by Feynman and Gell-Mann,[22] by Sudarshan and Marshak,[23] and Sakurai[24] which represent attempts to find a universal interaction for all decays involving four fermions, all require the VA combination.

THEORY

In the usual theories of allowed beta decay the probability of the emission of an electron-neutrino pair is given by

$$P(W,\theta_{e\nu})dWd\Omega = A_1F(A,W)pW(W_0-W)^2 \times[1+b/W+(\lambda p/W)\cos\theta_{e\nu}]dWd\Omega, \quad (1)$$

where A_1 is a proportionality constant, W and p,

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[7] B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955).

[8] J. Csikai and A. Szalay, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1959).

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[20] Barnes, Fowler, Greenstein, Lauritsen, and Norberg, Phys. Rev. Letters **1**, 328 (1958).

[21] B. W. Ridley, Nuclear Phys. **6**, 34 (1958).

[22] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[23] E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. **109**, 1860 (1958).

[24] J. J. Sakurai, Bull. Am. Phys. Soc. **3**, 10 (1958).

respectively, are the total energy and momentum of the electron, and W_0 is the maximum energy of the beta spectrum. The angle between the directions of emission of the electron and neutrino is $\theta_{e\nu}$ and the angular correlation coefficient is represented by λ. The units are as usual in beta decay; $\hbar=c=m=1$. For the analysis of nuclear recoil experiments it is convenient to transform the original $P(W,\theta_{e\nu})$ distribution function into a $P(W,R)$ distribution, where R is the kinetic energy of the recoiling nucleus. The new distribution function expressed in terms of the total energy W of the beta particle and the kinetic energy R of the recoiling nucleus is given by

$$P(W,R)dWdR=A_2F(Z,W)\{W(W_0-W)+b(W_0-W)+\tfrac{1}{2}\lambda[2MR-W^2+1-(W_0-W)^2]\}dWdR. \quad (2)$$

In the derivation of Eq. (2) the kinetic energy of the recoiling nucleus has been assumed to be negligible in comparison with the energy of the electron or the neutrino. This assumption is valid in practically all recoil experiments. The explicit form of λ is[25]

$$\xi\lambda=(|C_v|^2+|C_v'|^2-|C_s|^2-|C_s'|^2)\langle 1\rangle^2+\tfrac{1}{3}(|C_T|^2+|C_T'|^2-|C_A|^2-|C_A'|^2)\langle\boldsymbol{\sigma}\rangle^2, \quad (3)$$

where

$$\xi=(|C_v|^2+|C_v'|^2+|C_s|^2+|C_s'|^2)\langle 1\rangle^2+(|C_T|^2+|C_T'|^2+|C_A|^2+|C_A'|^2)\langle\boldsymbol{\sigma}\rangle^2. \quad (4)$$

The symbols $\langle 1\rangle$ and $\langle\boldsymbol{\sigma}\rangle$, respectively, denote the nuclear matrix elements for the (S,V) and (T,A) interactions. The unprimed and primed constants, respectively, represent the relative strengths of the parity-conserving and parity-nonconserving interactions. It is readily seen from Eq. (4) that λ assumes the values $+1$, -1, $+\frac{1}{3}$, and $-\frac{1}{3}$ for the pure V, S, T, and A interactions, respectively. It is also evident that λ does not contain terms due to the interference between parity-conserving and parity-nonconserving interactions. Therefore electron-neutrino angular correlation experiments of the type discussed in this paper are not able to separate the primed and unprimed coupling constants. In other words, these experiments are not sensitive to parity effects and cannot show the degree of mixing of the parity-conserving and parity-nonconserving interactions.

Recent experiments[15,16] show that the magnitude of the longitudinal polarization of the electrons emitted in beta decay is approximately equal to the maximum amount, v/c. The sense of the polarization is negative for negative electrons and positive for positrons. These results require the following choice of coupling constants:

$$C_{S,T}=-C_{S,T}' \quad\text{and}\quad C_{V,A}=+C_{V,A}'. \quad (5)$$

An upper limit to the magnitude of the Fierz interference term appears to be about 10^{-1}. For example, measurements[26] of the ratio of electron capture to positron emission in Gamow-Teller type decays indicate that $|b|<6\times10^{-2}$. Similar measurements[27] for a Fermi type show that $|b|<6\times10^{-2}$. An interesting result of the choice of coupling constants in (5) is that b becomes identically zero. In view of these considerations, we shall neglect the interference term in our analysis of electron-neutrino recoil experiments. A small energy-dependent Coulomb correction term which was omitted in the expression for λ given in Eq. (3) also becomes identically zero by this choice of coupling constants. This correction term vanishes in any case if the beta-decay process is invariant under time-reversal. The result of the time-reversal experiment presently being conducted by Clark *et al.*[28] using polarized neutrons is consistent with time-reversal invariance and suggests that full violation does not occur.

EXPERIMENTAL PROCEDURE

A. Apparatus

The design of the apparatus for this experiment was dictated by the requirement that the rate of collection of data should be as high as possible; that is, it should be limited only by the available amount of activity. This requirement rules out the conventional method of measuring the recoil spectrum, in which the flight time of the recoil ion is measured in coincidence with the associated beta particle. The time-of-flight or coincidence experiments are severely limited by chance coincidences at higher counting rates. Fortunately the recoil energy spectrum is the only information needed to deduce the angular correlation coefficient, λ, and from λ the nature of the beta-decay interaction can be determined. Thus the present experiment was designed

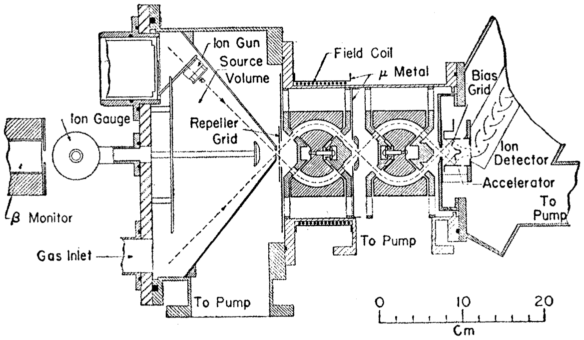

FIG. 1. Cross section of the recoil chamber showing the differential pumping system and the flight paths (dotted lines) of the recoil ions.

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[25] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[26] R. Sherr and R. H. Miller, Phys. Rev. **93**, 1076 (1954); Drever, Moljk, and Scobie, Phil. Mag. **1**, 942 (1956).

[27] J. Scobie and G. M. Lewis, Phil. Mag. **2**, 1089 (1957).

[28] Clark, Robson, and Nathans, Phys. Rev. Letters **1**, 100 (1958).

to measure the energy spectrum of the recoil ions without detection of the associated beta particles.

The vacuum chamber consisted of the source volume, the spectrometer chamber, and the recoil-ion detector as shown in Fig. 1. The radioactive gas was introduced directly into the source volume which was defined by an aluminum cone and a set of baffles. A small (7 mm) aperture in the apex of the cone was located at one focus of the spectrometer system. The baffle just behind the aperture helped to reduce the pumping speed and prevented recoiling ions from entering the spectrometer system at any angle outside the solid angle of acceptance of the spectrometer system.

The two spherical electrostatic spectrometers were mounted in the central section of the vacuum chamber. A second aperture at the common focus of the two spectrometers was effective in providing an additional stage of differential pumping between the source and the ion detector. The necessity of having this extra stage of differential pumping was the only reason for adding the second spectrometer. Three 300-liter/sec diffusion pumps were used in the differential pumping system to reduce the background from decays in or near the multiplier assembly. This background was measured by applying a retarding potential during one-half of each run to the grid which was located just outside the aperture of the source volume. The repelling voltage was made sufficiently high to stop all the recoil ions which came from the source volume. During the experimental observations a switching system automatically switched the retarding potential on and off and simultaneously switched the output from the ion counter into separate scaling circuits. The difference between the totals of the two scalers at the end of a run represented the true effect for a given energy setting of the spectrometers. The runs were timed by using a beta-sensitive counter to monitor the activity in the source volume. The beta counter also was switched between two scalers by the automatic switching system in order to monitor separately the activity present during the partial runs with and without the retarding potential.

Two special problems occurred in the detection of the negative recoil ions associated with positron emission. The first difficulty was caused by the fact that low-energy electrons were transmitted by the electrostatic spectrometer system in exactly the same manner as recoil ions of the same kinetic energy. Since electrons were detected at the low-energy end of a recoil spectrum, an axial magnetic field was generated in the first spectrometer by a coil wound around the outside of the vacuum chamber. Tests made with the ion gun positioned in the source volume as shown in Fig. 1 and with an electron gun mounted in the same position showed that the magnetic field effectively stopped all electrons but did not affect significantly the transmission of ions.

The second problem associated with the negative charge of the recoil ions was caused by the background that electrons caused in the ion detector. The recoil ions were detected by an electron multiplier with a specially constructed first stage that consisted of a cylindrical dynode with a set of grids for the acceleration of the ions. Unfortunately, in the case of negative-ion detection, the high-field emission of electrons from the grid system created an intolerable background at an accelerating voltage less than the value required for a counting efficiency of 100%. Since the recoil ions could not be detected with an efficiency of 100%, it was essential that all ions had the same total kinetic energy when they hit the cylindrical dynode so that the detection efficiency would not be energy dependent. In order to keep the total energy of the ions constant, the accelerating voltage was adjusted with every setting of the electrostatic spectrometer system. In the case of the He^6 and Ne^{23} experiments in which positive ions were detected, it was possible to use about 4 kv on the accelerator system. Tests indicated that nearly 100% of the recoil ions were detected and that the energy of the ions was not critical. However as a safety measure, the accelerating voltage was varied with every spectrometer setting.

The ion detector used in all the experiments described in this paper was constructed from AgMgNi alloy which was activated in an oxidizing atmosphere at a temperature of about 600°C. Several checks were devised to test the response of the multiplier system. The ion source shown in the source volume was modified at various times so that it emitted positive or negative argon ions, negative chlorine ions which are the same as the recoil ions from the decay of A^{35}, and positive lithium ions which are equivalent to the recoil ions from He^6. Extensive tests were made with each type of ion with the same voltages on the accelerating grids and spectrometer lenses as were actually used in the respective experiments. The counting efficiency of the detector for both negative and positive ions was measured at various ion energies. The efficiency was found to be constant within the instrumental accuracy of 10% for both negative chlorine ions and the positive lithium ions.

B. Production of He^6, Ne^{19}, Ne^{23}, and A^{35}

Both Ne^{19} and A^{35} were made by the cyclotron bombardment of SF_6 gas. In addition, SF_6 was employed as the carrier gas for the He^6 and Ne^{23} activities which were produced by neutron bombardment of beryllium oxide and sodium carbonate, respectively. The advantage of SF_6 is that the fraction which is dissociated under cyclotron or reactor bombardment produces substances which react strongly with the metal tubes of the gas handling system and, as a result, do not pass through the traps except in small quantities. A liquid nitrogen trap separated the SF_6 carrier from the noble gas activities. Upon removal of the liquid nitrogen from the trap the solid SF_6 sublimed and was recirculated

TABLE I. Summary of data for the production and identification of the radioactive noble gases for neutrino recoil measurements.

Exp.	Production	Decay	Half-life (sec)	Half-life (sec) measured	Impurity (max)
A^{35}	$S^{32}(\alpha,n)A^{35}$	Cl^{35}, β^+, ν	1.83 ± 0.03[a]	1.83 ± 0.02	3% Ne^{19}
Ne^{19}	$F^{19}(p,n)Ne^{19}$	F^{19}, β^+, ν	17.7 ± 0.2[b]	17.4 ± 0.2	None
He^6	$Be^9(n,\alpha)He^6$	Li^6, β^-, $\bar{\nu}$	0.85 ± 0.03[c]	0.83 ± 0.02	1% N^{16}
Ne^{23}	$Na^{23}(n,p)Ne^{23}$	Na^{23}, β^-, $\bar{\nu}$	37.6 ± 0.1[b]	37.5 ± 0.1	1% N^{16}

[a] Kistner, Schwarzschild, and Rustad, Phys. Rev. **104**, 154 (1956).
[b] J. R. Penning and F. H. Schmidt, Phys. Rev. **105**, 647 (1957).
[c] See reference 7.

through the target. By using two traps in parallel, it was possible to freeze gas in one trap during the warm-up period of the other trap, thus permitting continuous operation. A trap which contained heated chips of calcium metal was placed between the nitrogen traps and the source volume. This trap was expected to remove chemically active, radioactive gases. In the Ne^{19} and A^{35} experiments the calcium trap was merely precautionary since it was impossible to create positron emitters with energies and half-lives which could be confused with those of the desired activities. However, it was necessary to use the calcium trap to remove N^{16} from the He^6 and Ne^{23} activities. The neutron bombardment of the oxygen in the Be_2O and Na_2CO_2 and of the fluorine in the SF_6 formed N^{16} which was successfully removed by the calcium when the furnace was heated to about 550°C.

Half-life measurements were made of the different activities to help identify them and to detect the presence of impurities. Pertinent information concerning the properties and the production of the radioactive gases is contained in Table I. An additional proof of the degree of purity of the gases was provided by the fact that recoil ions were not observed beyond the ends of the expected recoil energy spectra.

Attempts were made to measure the effect of the pressure of the residual gas in the system on the recoil spectra of the four radioactive gases. Since the operating pressure in the source volume varied from 3×10^{-5} to 1×10^{-4} mm Hg and since the pressure in the rest of the system usually was less than 5×10^{-6} mm Hg, any effect of the residual gas would have occurred chiefly in the source volume. The effect of the residual gas would have been exhibited in two ways: as a shift of the high-energy end of a recoil spectrum toward the lower regions of the spectrum due to collisions between recoil ions and gas molecules at thermal energies; and as a neutralization of the charge of the recoil ions due to collisions with molecules or free electrons. Cross sections for the sum of the two collision effects have been measured[29,30] for Cl^- ions and for Na^+ and Li^+ ions in various gases. According to these observations, the cross sections varied with the energy of the ions, but did not exceed a value of about 2×10^{-15} cm^2 in the energy range of the present recoil experiments. Using 2×10^{-15} cm^2, we calculated that the maximum total collision probability ranged from 2 to 7% for recoil ions traversing an average path length in the source volume when the pressure varied from 3×10^{-5} to 1×10^{-4} mm Hg. In order to determine the actual effect of collisions on the recoil spectra, angular correlation measurements were made at different pressures in the A^{35} and He^6 experiments. No variation in the values of the angular correlation coefficients was observed when the pressure was changed by a factor of five. We conclude that the pressure of the residual gas did not introduce additional experimental errors greater than the statistical limits quoted for the values of the angular correlation coefficients.

ANALYSIS OF THE RECOIL SPECTRA

A. Theoretical Spectra

The experimentally determined recoil spectra were analyzed by comparison with the theoretical spectra predicted for various assumed values of the angular correlation coefficient.[31] The comparison was made by a least squares analysis, using the angular correlation coefficient and a normalizing coefficient as the parameters.

Theoretical spectra corresponding to $\lambda=-1$ and $+1$, the extreme limits of the angular correlation coefficient, were computed for each transition. For convenience in analyzing the recoil spectra the necessary corrections were applied to the theoretical rather than to the experimental spectra. Corrections for the Coulomb effect, the presence of branch transitions with gamma-ray emission as in the cases of A^{35} and Ne^{23} and the effects caused by the finite transmission of the spectrometer system were applied to the spectra.

The distribution functions used in the analysis of the recoil spectra are obtained from Eq. (2) by setting $\lambda=-1$ or $+1$ and have the following forms:

$$P_1(W,R)dWdR = A_3F(Z,W)(W_0^2-1-2MR)dWdR, \quad (6)$$

or

$$P_2(W,R)dWdR = A_3F(Z,W) \times(4WW_0-4W^2-W_0^2+1+2MR)dWdR. \quad (7)$$

In order to obtain the recoil energy spectra, these distribution functions were integrated between the upper and lower limits of the energy of the beta particles as specified by conservation of linear momentum and energy. The correction for the Coulomb effect was simplified somewhat by introducing the relation

$$F(Z,W)=F(Z,\infty)[1-\Phi(Z,W)], \quad (8)$$

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[29] B. M. Dukelvsky and E. Y. Zandberg, Zhur. Eksptl. i Teoret. Fiz. **21**, 1270 (1951).

[30] C. Ramsauer and O. Beeck, Ann. Physik **87**, 1 (1928).

[31] O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 9 (1954).

where $F(Z,\infty)$ is the correction factor corresponding to electrons with $W>W_0$. With this substitution the integration of Eq. (6) and Eq. (7) over W could be carried out in two steps. For the first step, the integration was carried out algebraically with $F(Z,W)=1$. The second integration was carried out graphically with $\Phi(Z,W)$ as the correction factor.. The magnitude of $\Phi(Z,W)$ was less than unity during the greater part of the integration.

The advantage of this method is that the basic accuracy of the algebraic integration of $P_{1,2}(W,R)dW$ is retained. Since the magnitude of the integral obtained by numerical integration was considerably smaller than that of the first integral, the over-all accuracy does not depend critically upon the accuracy of the Fermi functions or the numerical integration process. The values of the Fermi functions were taken from the tables of Rose.[32] The general expression for the shape of the recoil energy spectra expressed in terms of the integrated values of $P_{1,2}(W,R)dW$ can now be expressed as

$$N(R)dR=A_4\{N_1(R)+N_2(R)+\lambda[N_2(R)-N_1(R)]\}dR. \quad (9)$$

B. Low-Energy Branches of A^{35} and Ne^{23}

There are two weak positron branches in addition to the main transition in the decay of A^{35}. A 2% positron branch with a maximum kinetic energy of 3.2 Mev followed by a 1.76-Mev γ ray and a 5% positron branch with a 3.74-Mev maximum energy followed by a 1.22-Mev γ ray have been reported by Kistner *et al.*[33] Since the shell model suggest spins of $\frac{1}{2}$ and $\frac{5}{2}$ for the first two excited states of Cl^{35}, the low energy branches probably decay from the initial $J=\frac{3}{2}$ state of A^{35} according to Gamow-Teller selection rules. The recoil energy spectra used in the computation of the angular correlation coefficient for A^{35} include a correction for the presence of these low-energy branches. The magnitude of the correction amounts to about one-half of the statistical error in the measured value of λ with the assumption of either the tensor or axial-vector interactions.

Ne^{23} decays[34] by negatron emission with about 99% of the transitions going to the ground and first excited states of Na^{23}. The maximum electron energies and branching ratios of the transitions to the ground and first excited state are 4.39 Mev (67±3%) and 3.95 Mev (32±3%), respectively. The decay to the first excited state is followed by the emission of a single 436-kev gamma ray. The beta decay is an allowed one: the decay to the ground state is a pure G-T transition ($\Delta I=1$, no charge in parity) while the decay to the first excited state would allow a mixture of Fermi and G-T transitions ($\Delta I=0$, no change in parity). However, theoretical considerations predict that a change of isotopic spin accompanies the decay to the first excited state resulting in a strong predominance of the G-T decay.[21] In the analysis of this experiment, the transition to the first excited state was therefore assumed to be pure G-T. The very weak transitions to higher levels were neglected. The recoil spectra from the ground-state decay and the excited-state decay are added in the proportions of their intensities and the combined spectrum is used in the determination of the angular correlation coefficient.

C. Transmission of the Spectrometer and the Expected Recoil Energy Spectra

In order to compute a recoil energy spectrum which could be compared directly with the experimental results, corrections for the transmission of the spectrometer were combined with the corrections mentioned in the previous sections. Tests with argon ions showed that the transmission function of the spectrometer had the shape of a symmetrical trapezoid with a full width at the base of 8% and a full width at the top of 3% of the mean energy transmitted.

The distribution function to be directly compared with the experimental data can be expressed as

$$G(R_i)=\int S(R,R_i)N(R)dR,$$

where the transmission function $S(R,R_i)$ is centered about the recoil energy $R=R_i$. The integration is simplified if $N(R)$ is expanded about R_i in a Taylor's series. After the integration over the transmission curve has been performed, the distribution function becomes

$$G(R_i)\cong AR_i\{N(R_i)+6\times10^{-2}(R_i/R_{\max})^2\times[N(R_{i+1})+N(R_{i-1})-2N(R_i)]+\cdots\}, \quad (10)$$

where the distance between consecutive values of $N(R_i)$ is $0.05R_{\max}$ and A is a normalizing constant. The most important term in $G(R_i)$ is the original distribution function of Eq. (9) multiplied by the recoil energy to compensate for the fact that the transmission is proportional to the recoil energy. The remaining terms are small and depend on the second and higher derivatives of $N(R)$ with respect to R and represent the correction for the finite width of the transmission function. The effect of the finite transmission band of the spectrometer is most significant where there are sharp changes in the slope of the recoil spectrum. In this group of experiments the effect of the transmission band was noticeable only at the high-energy end of a given spectrum where the band width was at a maximum.

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[33] Kistner, Schwarzschild, and Rustad, Phys. Rev. **104**, 154 (1956).

[34] J. R. Penning and F. H. Schmidt, Phys. Rev. **105**, 647 (1957).

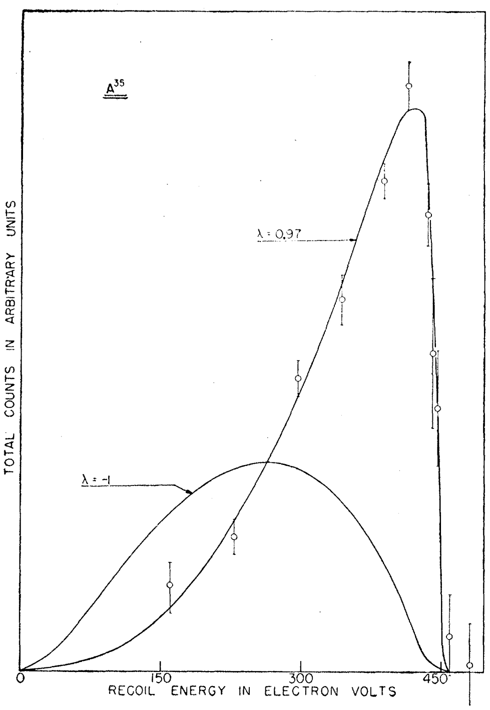

FIG. 2. Energy spectrum of the recoil ions from the positron decay of A^{35}. The angular correlation $\lambda = +0.97 \pm 0.14$ is consistent with either the AV or the TV combination of interactions.

The correction for the width of the transmission band has been made to all recoil curves and is apparent only as a small asymptotic tip just above the maximum recoil energy.

D. Least-Squares Analysis of the Recoil Spectra

The recoil ion energy spectrum for each activity was measured by making repeated measurements of the recoil counting rate at a series of spectrometer energy settings. The calibration of the spectrometer system against an absolute energy scale was not critical because the shapes of the recoil spectra do not depend strongly on the magnitude of the maximum recoil energy. Since the high-energy limit of each recoil spectrum was almost a vertical straight line, a few measurements were sufficient to determine the absolute energy scale to the desired accuracy. However, the relative position of each of the points on the energy scale was determined as accurately as possible using a potentiometer system.

The statistical errors used in all parts of the least-squares calculations and the errors finally reported for the angular correlation coefficients are the so-called "standard errors," with a probability of 68% for a subsequent measurement falling within the given limits. The normality of the distribution of the recoil counts at the various energy settings was checked by the chi-square test. The probability of finding a larger deviation from the mean in a subsequent experiment, as determined by the chi-square test, was between 0.9 and 0.1 for all the points used in the least-squares analysis.

Using A_4 and λ of Eq. (9) as least-squares parameters, the best fit between the corrected theoretical curve and the experimental data was chosen by the usual application of the method of least squares.[35] The experimental points were weighted inversely according to their respective statistical errors. The error in λ was determined by weighting the accuracy of each experimental point N_i by the sensitivity of λ to the shape of the recoil spectrum according to the relation

$$\sigma(\lambda) = \left[\sum_i \sigma(N_i)\left(\frac{\partial\lambda}{\partial N_i}\right)\right]^{\frac{1}{2}}. \tag{11}$$

If the experimental point was further from the best fitting curve than the statistical error, the deviation from the curve is used in Eq. (11) instead of the statistical error.

EXPERIMENTAL RESULTS

The experimental data and the theoretical recoil energy distributions for the positron decay of A^{35} are shown in Fig. 2. The solid curve drawn through the experimental points corresponds to an angular correlation factor of $\lambda = +0.97 \pm 0.14$ which is in excellent

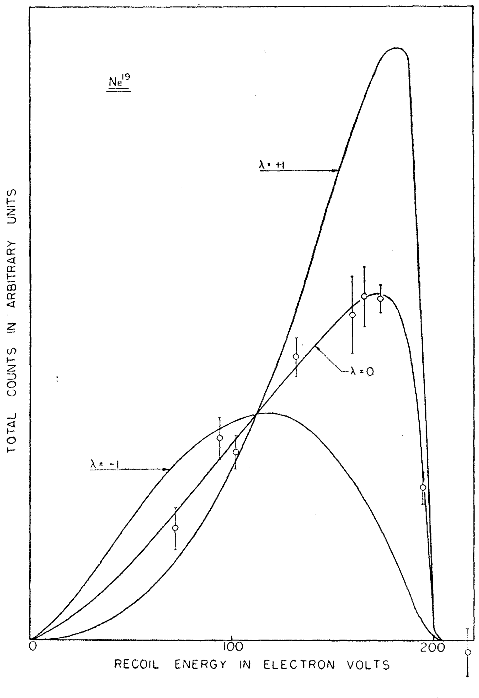

FIG. 3. Energy spectrum of the recoil ions from the positron decay of Ne^{19}. The angular correlation $\lambda = 0.00 \pm 0.08$ is consistent with either the ST or VA combination of interactions.

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[35] Yardley Beers, *Introduction to the Theory of Error* (Addison Wesley Press, Cambridge, 1953).

agreement with the value of $+0.89\pm0.08$ predicted for the *AV* interaction or the value of $+0.94\pm0.04$ expected for the *TV* interaction. In each case the predicted values of the angular correlation coefficient were deduced from known *ft* values.

In order to check the reliability of the double spectrometer used in the A^{35} experiment, the energy spectrum of the recoils from the positron decay of Ne^{19} was measured with this spectrometer. The Ne^{19} recoil energy spectrum is shown in Fig. 3. The experimentally determined angular correlation is $\lambda=0.00\pm0.08$ which is to be compared with -0.06 ± 0.02 for the *ST* interaction or $+0.06\pm0.02$ for the *VA* interaction. The close agreement between the measured and predicted values of λ indicated that our spectrometer was entirely reliable. Unfortunately, the accuracy of the Ne^{19} data is not sufficient to distinguish between the *ST* and *VA* interactions.

The negatron decay of He^6 probably is the most noted example of an allowed, pure, G-T transition. The recoil spectrum from this decay was measured in the double spectrometer after the conclusion of the A^{35} and Ne^{19} experiments. The experimental data for He^6 and the spectra predicted for various values of the angular correlation are shown in Fig. 4. The points between 700 and 1400 ev were fitted to a curve corresponding to an angular correlation $\lambda=-0.39\pm0.05$. The result of this experiment clearly indicates that the dominant G-T interaction is axial-vector.

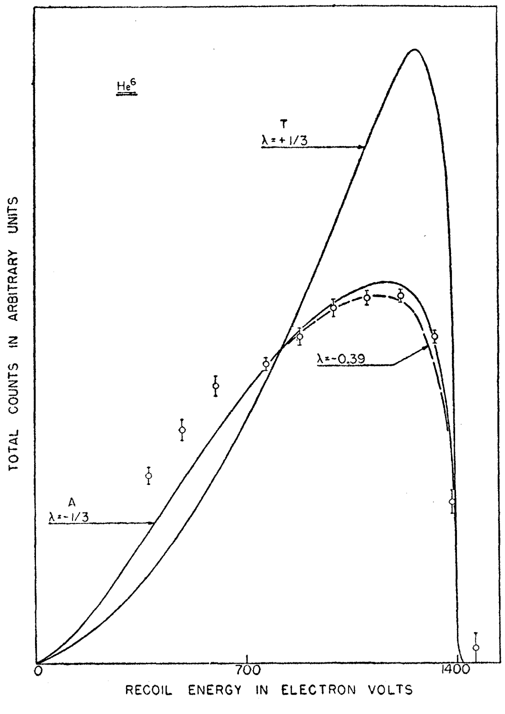

FIG. 4. Energy spectrum of the recoil ions from the negatron decay of He^6. The dashed curve represents the best fit with the data. The experimental points below 700 ev include counts from multiply charged ions and were not used in the computation of λ.

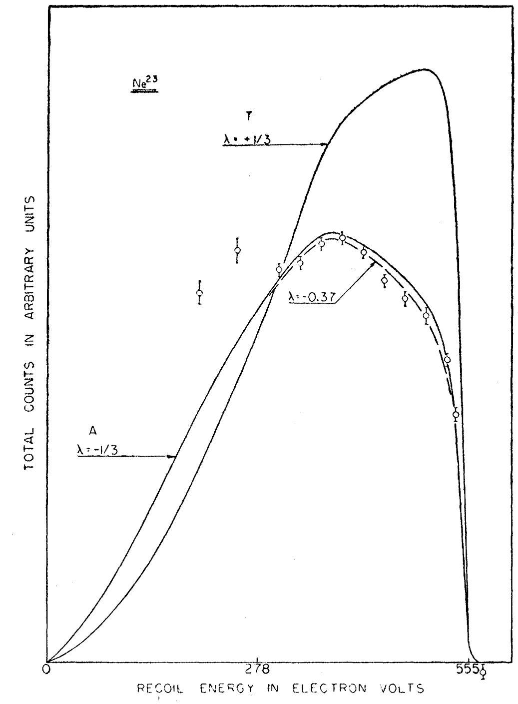

FIG. 5. Energy spectrum of the recoil ions from the negatron decay of Ne^{23}. The experimental points below the mid-energy include counts from multiply charged ions and were not used in the computation of λ. The dashed curve represents the best fit with the experimental data.

As mentioned earlier the negatron decays of Ne^{23} to the ground and first excited states of Na^{23} very likely are examples of nearly pure G-T transitions. The energy spectrum of the recoil ions from the decay of Ne^{23} is shown in Fig. 5. The angular correlation deduced from the shape of the curve between 278 and 555 ev is $\lambda=-0.37\pm0.04$ which supplies additional evidence that the G-T interaction is axial-vector. The results also verify the initial assumption that the decay to the first excited state of Ne^{23} is predominantly G-T since any admixture of a Fermi transition would lead to a value of λ less negative than $-\frac{1}{3}$.

The recoil spectra of both He^6 and Ne^{23} exhibit secondary spectra due to multiply charged ions in the region below the median energy. Since the spectrometer system is electrostatic, doubly charged ions are transmitted at a voltage setting corresponding to singly charged ions of twice the kinetic energy. Consequently, the points below the median energy will include multiply charged ions. This problem does not occur in the positron decays of A^{35} and Ne^{19} because the loss of an electron neutralizes the negative recoil ion before transmission. Higher states of ionization will convert the negative ions to positive ions which will not be transmitted. However, if the probability of ionization

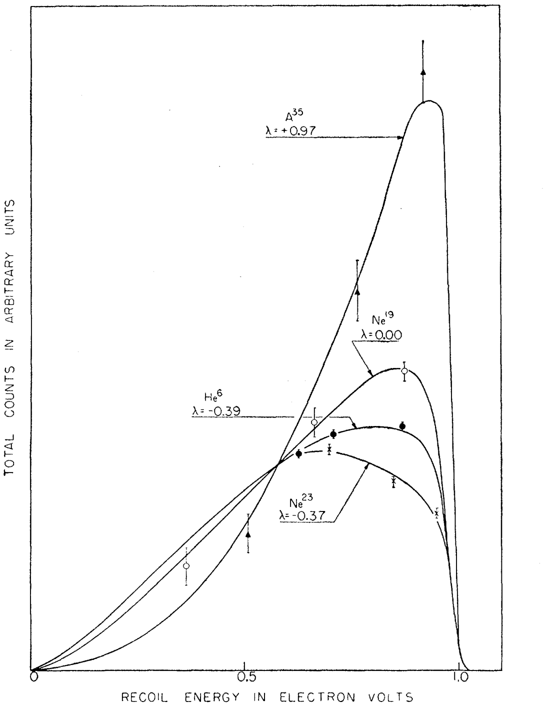

FIG. 6. The results of the A^{35}, Ne^{19}, Ne^{23}, and He^6 experiments with the curves selected by a least-squares analysis. The points shown are representative samples of the experimental data given in the four preceding figures. Approximately 5×10^4 to 1×10^5 true counts were recorded per datum point.

depends strongly upon the velocity of the recoiling ion, the recoil spectrum could be seriously distorted before transmission.

Winther[36] has made a theoretical investigation of the ionization accompanying the beta decay of He^6 and has concluded that the dominant effect for light nuclei is the shaking off of an atomic electron as a result of the sudden change of the nuclear charge. The transition probabilities should be corrected for the motion of the recoiling nucleus. In the case of the lithium recoils from the decay of He^6 he estimates this correction to be of the order $(v/v_0)^2\approx0.003$, where v is the velocity of the nuclear recoil and v_0 is the velocity of the atomic electrons. Since the ionization probability for light atoms is approximately 10%, the correction for the recoil motion probably can be neglected. If this assumption is correct, the recoil energy spectrum of the singly charged ions observed in each of our experiments is representative of the spectrum of ions of all possible charge states including zero.

In the case of the He^6 recoil spectrum of Fig. 4, if we assume for each of the three points below 700 ev that the counts in excess of the values corresponding to a spectrum characterized by $\lambda=-0.39$ are due to multiply charged ions, we find an ionization probability of $(29\pm15)\%$. This is considerably higher than the value of $(10.5\pm1.5)\%$ predicted by Winther. A possible explanation for this discrepancy is that the multiply charged ions were counted more efficiently than the singly charged ions because the former experienced twice the acceleration in the grid system of the electron multiplier.

The results of the four recoil experiments and the predicted recoil energy spectra are displayed in Fig. 6. The points are representative samples of the experimental data given in the preceding figures. The experimental data are presented in a different manner in Fig. 7 where the angular correlation coefficients are plotted against the fraction F of the decays which are allowed by Fermi selection rules. Since the correlation coefficient λ is a linear function of F, the experimental values should lie on a straight line if each decay is described by the same combination of interactions. The data for evaluating F are obtained from experimental ft values. The angular correlation for the neutron decay as measured by Robson, is included for comparison with our results. Although there is no serious discrepancy between the data, it is evident that the value for the neutron is displaced from the VA curve by an amount equal to the total error quoted by Robson.

CONCLUSIONS

The identification of the dominant interactions in allowed beta decay has been the purpose of these four experiments. The consistent experimental results now clearly indicate that the dominant combination of interactions is VA. Unfortunately, the precision of the

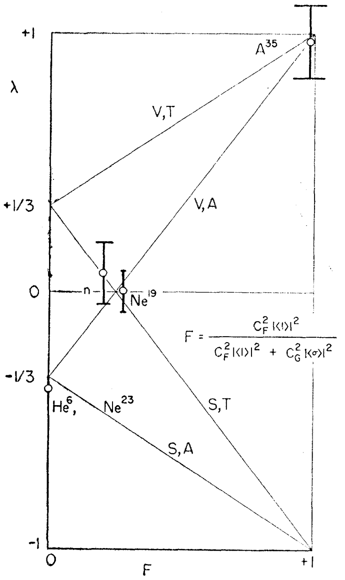

FIG. 7. The angular correlation coefficients plotted against the fraction of the decays which are allowed by Fermi selection rules. The height of the bars is twice the standard error in λ. The length of the horizontal bars is twice the uncertainty in F. The angular correlation for the neutron decay as measured by Robson[9] is included. The five experimental values of λ are compatible with the VA assumption.

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[36] A. Winther, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 27, No. 2 (1952).

present method is limited by the fact that the spectra of singly and multiply charged recoil ions cannot be studied separately. In addition, a small correction for the energy dependence of the probability of ionization of the recoil atoms should be applied. We conclude that the limited accuracy of our present experiments rules out an admixture of more than 10% of either the tensor or scalar interactions with the *VA* combination.

ACKNOWLEDGMENTS

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Decay of U^{240} and 7.3-min Np^{240}†

M. E. Bunker, B. J. Dropesky, J. D. Knight, J. W. Starner, and B. Warren
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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The radiations of U^{240} and 7.3-min Np^{240} have been studied with a solenoidal beta spectrometer, beta- and gamma-scintillation spectrometers, and 180° permanent-magnet spectrographs. The principal decay branch of U^{240} is a 0.36-Mev beta transition to the 7.3-min state of Np^{240}. The only other radiations observed which are attributed to U^{240} are the conversion lines associated with a 0.044-Mev transition.

The decay scheme of 7.3-min Np^{240} is considerably more complicated than that indicated by previous investigations. On the basis of coincidence studies, intensity data, internal conversion coefficients, and the measured transition energies, a consistent level scheme for Pu^{240} is proposed which has excited states at 0.043, 0.142, 0.597, 0.858, 0.900, 0.942, 1.42, 1.53, and 1.62 Mev. The ground-state transition from the 0.858-Mev level is of $E0$ multipolarity, identifying this level as a 0+ state. There are beta transitions to the ground state of Pu^{240} ($Q_\beta = 2.18$ Mev) and to each of the above excited states except the one at 0.142 Mev. Consideration of the beta-decay information leads to a spin and parity assignment of 1+ for 7.3-min Np^{240}. Various features of the decay scheme are compared with the predictions of current models of nuclear structure.

I. INTRODUCTION

Spectrometric examination of the β and γ radiations of 14.1-hr U^{240} and its daughter nuclide, 7.3-min Np^{240}, was first reported in 1953.[1] The continuous β-ray spectrum associated with these two activities (in equilibrium) was resolved into β groups with end-point energies of 2.156, 1.59, 1.26, 0.76, and 0.36 Mev. It was proposed that the 0.36-Mev group represents the U$^{240} \rightarrow$ Np^{240} (7.3 min) transition, and that the 2.156-Mev group represents the Np^{240} (7.3 min) $\rightarrow$ Pu^{240} ground-state transition. Assignment of the remaining β groups as representing transitions to excited states of Pu^{240} was supported by scintillation measurements which indicated that γ rays of energies $\sim$0.56, $\sim$0.90, and $\sim$1.40 Mev accompany the decay of Np^{240}.

More recent investigations have shown that the 7.3-min Np^{240} decay scheme is considerably more complex than the one outlined above. Measurements of internal-conversion electron spectra and γ-ray scintillation spectra[2,3] have established the existence of γ-ray transitions of energies 0.0429, 0.557, and 0.600 Mev (presumably associated with the de-excitation of levels at 0.0429 and 0.600 Mev in Pu^{240}), and have provided evidence for "complexes" of γ rays at $\sim$0.85 and $\sim$1.5 Mev.

Additional information on the energy levels of Pu^{240} has been obtained from studies of the radiations which accompany β decay of the 63-min isomer of Np^{240} [4–6] (which is not formed in the decay of U^{240}), electron-capture decay of Am^{240},[7,8] and α decay of Cm^{244},[9–11] but thus far it has not been possible to synthesize all of the known data into a consistent level scheme.

As additional source material has become available at this Laboratory at various times subsequent to the initial report,[1] we have been able to make further studies of the radiations of U^{240} and 7.3-min Np^{240}.

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† Work done under the auspices of the U. S. Atomic Energy Commission.

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