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Measurement of Angular Correlations in the Decay of Polarized Neutrons*

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The electron-momentum–neutron-spin correlation coefficient was found to be $A=-0.115 \pm 0.008$, and the antineutrino-momentum–neutron-spin correlation coefficient was found to be $B=1.00\pm 0.05$. The value of A leads to $|G_A/G_V|=1.26\pm 0.02$ for the ratio of Gamow-Teller–to–Fermi coupling constants in β decay, and B is consistent with zero scalar or tensor interaction.

I. INTRODUCTION

The ordinary $\Delta S=0$ β decays have been studied in numerous nuclei and several particles. Among the latter is the neutron, which, besides being free of the complications arising from nuclear structure, has the advantage that its decay shows both Fermi and Gamow-Teller transitions. Since neutrons are readily available and easily polarized, it is reasonable to try to determine a number of the fundamental parameters of the weak interaction from a study of the decay of free neutrons; and indeed a considerable effort has been devoted to this – beginning with Snell, Pleasonton, and McCord[1] at Oak Ridge and Robson[2] at Chalk River.

At present, there is special interest in determining the parameter $g_A=|G_A/G_V|$, where G_A and G_V are the Gamow-Teller (axial vector) and Fermi (vector) coupling constants, respectively, because (1) it would serve to check on the consistency of several measurements of the weak-interaction parameters, and (2) considerable progress has been made in theoretical understanding of the value – principally by Adler[3,4] and Weisberger.[5,6]

The situation at the beginning of this experiment is summarized in Table I. As seen in the table, the most accurate values of g_A are from the determinations of the neutron ft and the ft values of some pure Fermi transitions between isobaric states with $J=0^+$ and $T=1$ (in ^{14}O, ^{26m}Al, etc.). A number of the latter have the same ft values to a reasonable accuracy, and the matrix element can be evaluated from simple assumptions (e.g., charge independence of nuclear forces). However, one is entitled to some reservations as to whether the assumptions involved are good to the accuracy of the experimental values. Also, the recent remeasurement of the neutron half-life by Christensen *et al.*[7] gives $g_A=1.23\pm 0.01$, in disagreement with the older experiment by Sosnovskii *et al.*[8] which gave $g_A=1.18\pm 0.02$.

The neutron decay by itself is inherently an attractive possibility for determining g_A as well as other β-decay parameters because of the simplicity of the matrix elements. Unfortunately, the A value measured earlier at this laboratory[9] is not accurate enough to distinguish between the various theoretical or experimental values of g_A. Therefore, we have undertaken an improved measurement of A (the coefficient of asymmetry of electron momentum with respect to neutron spin) and of B (the coefficient of asymmetry of neutrino momentum with respect to neutron spin) in the decay of polarized neutrons. A preliminary report on this work has already been published.[10]

II. APPARATUS

The apparatus used in the experiment was basically similar to that used in the earlier measurements,[9] so in this description we will only go into details of the changes that have been made in that apparatus.

A new polarizer was built for this measurement. It is shown with the other parts of the apparatus, in Fig. 1. It consisted of two 20-cm × 160-cm cobalt mirrors mounted facing each other about 1 cm apart, with a spacer and beam stop between. The mirrors were magnetized with 14 000 ampere-turns, which was reduced to 6000 ampere-turns for steady operation. This required 1 kW of power. The mirrors and collimators were so arranged that the reflected beams crossed between the proton and β detectors, where the combined beams were approximately 1 cm wide and 30 cm high. The mean angle of reflection was about 7 min, hence critical reflection occurred for neutrons with wavelengths greater than about 1.4 Å provided their spin was parallel to the applied magnetic field. In the whole polarized beam there were about 3×10^8 neutrons/sec at the beginning of the experiment.

To preserve the surface of the mirrors, the polarizer assembly was placed in a vacuum tank as shown. Unfortunately, after a month in place in the reactor, the vacuum tank developed a large leak somewhere in the inaccessible section and it became necessary to go to a helium gas filling

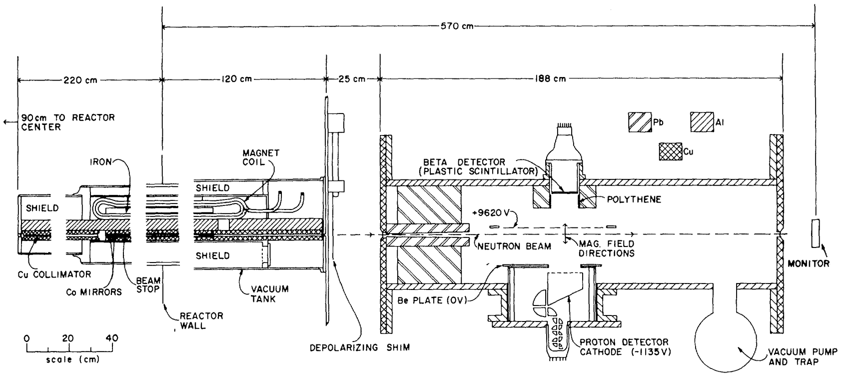

FIG. 1. A horizontal section through the apparatus used in measuring decays of polarized neutrons. The external shielding is omitted for clarity.

with a continuous flow of helium. This failed to protect the inner end of the copper collimator and the slot for the neutron beam gradually became closed by copper oxide powder. At the end of six months, the flux in the beam was down by a factor of 3 and the polarization was reduced significantly. Since repolishing the mirrors did not increase either the intensity or the polarization, we believe that both effects were caused by the copper oxide powder.

The polarization of the beam was measured with the aid of a Stern-Gerlach apparatus.[11] For the present purposes it was necessary to be sure that these measurements applied to the neutron density in our beam, i.e., to the sample seen by our decay detectors. This could have been done by using a thin $(1/v)$ ^{3}He counter with the Stern-Gerlach apparatus. However, to get reasonable counting rates, it was necessary to use more efficient counters, so measurements were made with two such counters which differed quite appreciably from each other in the way their efficiency varied with neutron energy. The fact that these counters gave identical results implies that the polarization did not vary appreciably with neutron energy. An extrapolation to zero efficiency ($1/v$ counter) was therefore not necessary.

TABLE I. Summary of measurements of g_A.

Basis of determination	g_A
A from decay of polarized neutrons	1.25 ± 0.05[a]
ft values for neutron decay and $0^+ \rightarrow 0^+$ transitions	1.23 ± 0.01[b,c] 1.18 ± 0.02[d]
a from neutron decay	1.22 ± 0.12[e]
Theory	1.24 ± 0.03[f] 1.15[g]

[a] Burgy *et al.*, Ref. 9.

[b] Christensen *et al.*, Ref. 7.

[c] J. M. Freeman, J. G. Jenkin, G. Murray, and W. E. Burcham, Phys. Letters 27B, 156 (1968).

[d] Freeman *et al.*, Ref. c; Sosnovskii *et al.*, Ref. 8.

[e] Grigor'ev *et al.*, Ref. 14.

[f] Adler, Refs. 3 and 4.

[g] Weisberger, Refs. 5 and 6.

Because the Stern-Gerlach apparatus accepted a very small beam (about 0.15 mm high by 3 mm wide), it was necessary to scan the beam and make measurements at about 25 places. This took several days and was done three times in the course of the experiment with the following results.

Run No.	Polarization
1	87% ± 3%
2	87% ± 3%
3	68% ± 12%

The standard deviations given apply to the 25 or so individual measurements (weighted for the intensity of the beam at each place) in the course of a scan. The statistical error for the average at a given date would be about a fifth of that shown. The change with time, however, makes for a serious uncertainty. We interpolated linearly between dates of the polarization measurements in reducing the data, and estimate that this makes the uncertainty in the polarization ±3%. The results of one horizontal scan in run No. 1 are shown in Fig. 2.

The depolarization shim was moved automatically in this experiment so that polarized and depolarized measurements alternated about every 2 min. The depolarizing shim reduced the intensity of the beam about 7%, but small-angle scattering effects were negligible.

The detector arrangements were relatively little changed from those in the first experiment. The principal improvements were in the magnetic guide field – which was made more uniform and easy to switch from horizontal to vertical (for a possible time-reversal experiment) by new coils – and in the proton detector. The proton detector was given a new cathode of Be-Cu, roughly 18 cm in diameter, and a set of heaters so that the cathode and first three dynodes could be heated to about 600°C. With one such treatment, the proton counter operated for six months in a vacuum of a few times 10^{-6} Torr produced by an old oil diffusion pump. During this time the output pulse heights from the counter decreased by a factor of 2, but the efficiency for counting protons declined by less than 10%. The magnetic shielding of the proton counter was improved sufficiently so that the efficiency of the counters was negligibly changed in reversing the magnetic field.

The electron detector was a Pilot B plastic scintillator (12.4 cm in diameter and 0.35 cm thick) viewed by an RCA-4525 photomultiplier through a Lucite light guide (15 cm long and 13 cm in diameter). The resolution width of this detector was 18% for 0.37-MeV electrons from a ^{113}Sn source. The magnetic shielding of the electron counter was sufficient to prevent the changes in magnetic field from influencing the response of the counter. Surfaces which could scatter electrons back into the electron detector were covered with low-Z materials (Be or polystyrene). This minimized in-scattering, which would otherwise have been a serious source of error in the asymmetry measurements. Even so, a correction of $+0.02 \pm 0.01$ was applied to the measurements of the B coefficient in order to correct the backscattering.

The electron and proton detectors were placed on a common axis perpendicular to the beam plane, as seen in Fig. 1 and schematically in Fig. 3. A uniform electric field to accelerate the decay protons toward the proton counter was created by applying a voltage (about 10 kV) between the entrance grid of the proton detector and a grid on the opposite side of the beam. The electrodes were big enough to ensure uniformity of the field in the region of interest. The field was parallel to the axis of the counters and to the magnetic guide field (polarization direction) to within 1°.

The decay events were identified as delayed coincidences between the electron and proton detectors, the delay being the flight time of the protons. The proton path was a parabola, and the time of flight depended on the initial proton momentum along the detector axis. With this particular arrangement, the flight time was between 225 and 360 nsec, depending on the electron and neutrino momentum components. The delayed-coincidence requirement greatly improved the signal-to-background ratio.

The electronic system was fairly standard. A sequence-sensitive time-to-pulse-height converter gave pulses of 0–10 V for proton delay times between −100 and +600 nsec. For each coincidence in this delay-time interval, the delay time, proton-counter pulse height, and electron-counter pulse height were converted to binary form and stored, event by event, on a 24-track magnetic-tape recorder.[12, 13] This gave us a $128 \times 32 \times 32$-channel analyzer (time, proton pulse, electron pulse) and furthermore allowed us a few bits to identify polarization direction, position of the depolarizing shim, etc., for each event. The main advantages of this recording system were: (1) Discriminator values could be changed after the experiment had been run. This was done when the tape was run through a search station which selected the events according to preset conditions on two of the three parameters of each event and sorted them according to

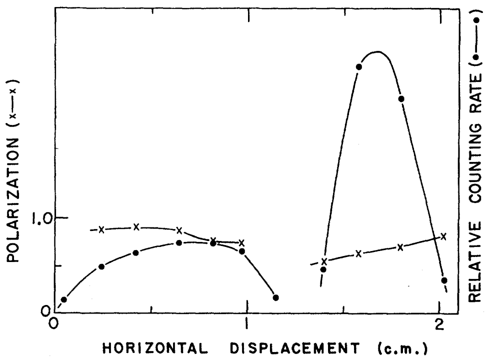

FIG. 2. Results of one scan of the beam in a polarization measurement. The horizontal displacements were measured about 6 m from the center of the mirror. The two peaks are the beams from the two polarizer mirrors. The beams have become separated at this distance.

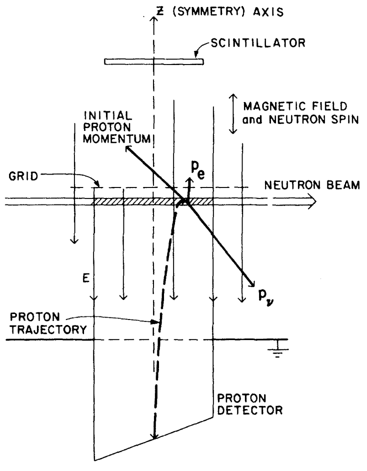

FIG. 3. Schematic diagram of the detector arrangement, showing a typical detectable neutron decay.

the third. (2) The system was very reliable. (3) The time spectrum was more finely divided than in the old system so that the width of the recording channels had almost no effect on the time resolution of the spectrum.

Typical experimental runs consisted of several days of measurements. The direction of polarization was changed only about once a week by reversing the guide field. A ^{3}He neutron counter intercepting a small part of the beam served as beam monitor.

III. CALCULATIONS

The probability distribution for the β decay of polarized neutrons is

$$W d\Omega_e d\Omega_\nu dE_e = N(E)\,\xi \left(1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\frac{\langle \vec{J}\rangle}{J}\cdot\frac{\vec{p}_e}{E_e} + B\frac{\langle \vec{J}\rangle}{J}\cdot\frac{\vec{p}_\nu}{E_\nu} + D\frac{\langle \vec{J}\rangle}{J}\cdot\frac{\vec{p}_e}{E_e}\times\frac{\vec{p}_\nu}{E_\nu}\right) d\Omega_e d\Omega_\nu dE_e . \qquad (1)$$

Here the $\vec{p}$'s and E's denote momenta and total energies, respectively; e and ν used as indices show which particle is involved; a, ξ, A, B, and D are parameters depending only on the β-decay coupling constants and nuclear matrix elements, and $\langle\vec{J}\rangle/J$ is the average polarization vector. We are concerned with measuring the parameters A and B. It is easy to see how our experiment can measure A. The electric field accelerates the protons and defines the "source volume" shown as the hatched area in Fig. 3. To a first approximation, all protons created inside this source volume are detected – independent of the electron and neutrino momenta. This means that the a and B terms in the counting rate will average out in integrating the probability distribution. Furthermore, the D term cancels completely. Therefore, only the term involving A is left. Since the electron detector detects electrons with momenta roughly parallel to the direction of polarization, this term will cause the counting rates for the two polarization directions to differ by approximately $2A(v/c)$.

That B can be found from the same data is seen from the following simple argument. Let us assume a positive polarization, i.e., that the neutron spin is directed towards the β counter in our sign convention. Furthermore, let B be positive. This means that on the average the neutrino will come out toward the β counter. Since the proton momentum is opposite to the sum of the electron and neutrino momenta, the protons will recoil more energetically for positive than for negative polarization. Therefore, the shift in average delay time from one sign of polarization to the opposite is a fairly sensitive measure of B. Moreover, the fixed position of the electron counter ensures that the electron asymmetry coefficient A has only a small effect on the average delay time.

Unfortunately a rather crude approximation was made above. The concept of "source volume" is much more complicated in the actual case. The effective source volume will depend not only on the point at which the event occurs, but also on the momenta of the decay particles. We have therefore used two different computer programs in kinematic calculations of the motions of the decay particles in the applied electric field. For neutrons decaying in the source volume, these programs calculate what fraction of the decays will eject a β particle into the β detector and a proton into the proton detector. This calculation is performed first for an unpolarized beam (for which in essence only conservation of four-momentum is used) and second for a polarized beam (for which the angular correlations must be considered). The calculated ratios of fractions collected in the polarized and in the unpolarized cases are then compared with the measured counting rates in the two cases and from this comparison the value of A can be found (on the assumption that $B = 0.99$).

To find B, the same programs can be used to calculate the average time of flight for the detected protons in the polarized and unpolarized cases and the procedure is very similar.

The source volume that must be integrated over in these calculations is the volume of the neutron beam in front of the detector. This volume is thin enough to be reasonably approximated by a plane. One program used the Monte Carlo technique and did approximately 10^5 decays, of which a few thousand hit the two detectors. The other was a numerical integration using 400 points in the source volume, 360 neutrino directions ($\sim 1/30$ sr each), and four β directions ($\sim 1/15$ sr each, because all four directions were restricted to paths entering the β counter) for each of ten β energies. These calculations also considered the effect of the β-momentum–neutrino-momentum correlation coefficient, a in Eq. (1), on the measurements of A and B. The value taken was $a = 0.1$, as given by the $V-A$ assumption which agrees with the measured value of a.[14] The two programs gave satisfactory agreement. The results, summarized in the expressions for the counting rate R and the average delay time $\bar{t}$ in terms of the polarization $\boldsymbol{P}$, the coefficients a, A, and B, and a constant K, are

$$R = K(1 - 0.05a + 0.730AP + 0.0118BP),$$

$$\bar{t} = 295\,\frac{(1 - 0.07a + 0.727AP - 0.0155BP)}{(1 - 0.05a + 0.730AP + 0.0118BP)}\ \text{nsec}.$$

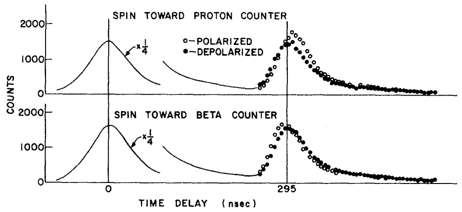

FIG. 4. The time spectrum obtained in the experiment. These are the data on small proton pulses and represents about three months of actual running time.

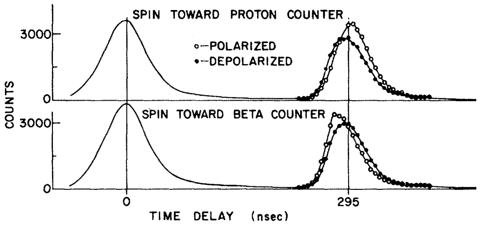

FIG. 5. The large-proton-pulse time spectrum, taken at the same time as Fig. 4.

These results apply to the 95–783-keV interval of β energies. It follows that the use of counting rates R to measure A involves corrections of about 15% for the term in B and less than 1% for the term in a. Likewise, determination of B from $\bar{t}$ involves corrections of about 8% for the A terms and less than 1% for the a terms.

IV. RESULTS

Figures 4 and 5 show time spectra obtained with the search station set to accept electron pulse heights corresponding to 95–783-keV electrons. Events involving small pulses from the proton counter appear in Fig. 4 while those with larger proton pulses appear in Fig. 5. Figure 6 is a semilog plot of the data of Fig. 5, including the very low channels which were omitted from the long-delay side of Fig. 5. In all, about 2×10^5 events (polarized and unpolarized) were used in calculating our final results.

The neutron decay peak in the data of Figs. 4 and 5 rides a small background of accidental coincidences. Corrections were calculated on the assumption that the background (well away from the prompt peak) was constant, and this point was checked by a run with a $^6\mathrm{LI}_2(\mathrm{CO}_3)$ shutter stopping the neutrons. On the other hand, in the case of small proton pulses (Fig. 4), the large background of accidental events prevented a useful (i.e., statistically significant) determination of B from these data but a value $A=-0.112\pm0.015$ was obtained. We believe that the agreement between this result and the result from larger proton pulses largely eliminates the possibility that a variation in the counting efficiency at different positions on the proton counter has introduced a serious systematic error into our results.

Table II shows a further breakdown of the data of Fig. 5 (large proton pulses). It is immediately apparent that the various results for A are consistent within the statistical uncertainties. The values of A from the two spin directions differ by about one standard deviation. Even if this were significant, it still would not be a matter of concern because it is possible that results for a single-spin direction could be affected by a systematic error that would not affect the over-all results. For instance, small-angle scattering could change the ratio of the efficiency of our neutron-beam monitor to that of the neutron-decay detection system, but this would cancel the same error in the other spin direction. The results for B are not so clearly consistent within statistical uncertainties. Hence, additional ways of looking at these data are presented in Table III. The results for the two spin directions agree very well, but the results for the two β-energy groups do not agree so well. We suspected that this might be a systematic effect associated with a drift in the gain of the β counter, but a check on the β spectrum associated with the delayed-coincidence peak

TABLE II. Results for different β energies and spin directions.

Spin direction	Toward β counter		Toward proton counter	
Range of β energies (keV)	95–320	320–783	95–320	320–783
Calculated time shift[a] (nsec)	−8.56	−4.60	7.56	3.95
Observed B[b]	0.89 ± 0.06	1.14 ± 0.11	0.99 ± 0.07	1.08 ± 0.13
$\langle(v/c)\cos\theta\rangle_{\mathrm{av}}$[c]	0.622	0.817	−0.662	−0.817
Observed A	-0.127 ± 0.023	-0.129 ± 0.021	-0.103 ± 0.023	-0.107 ± 0.021

[a] Calculated increase in proton collection time for a polarization of 0.81, assuming $B=0.99$ and $A=-0.115$.

[b] $0.99\times$(observed shift)/(calculated shift for $B=0.99$). The uncertainties do not include the ±0.03 uncertainty in the polarization.

[c] Here, v/c is the ratio of the electron velocity to the velocity of light and θ is the angle from the electron direction to the neutron spin direction.

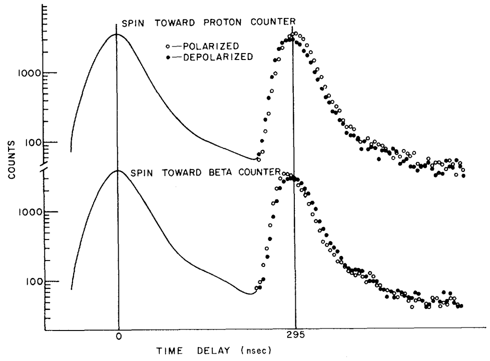

FIG. 6. A semilog plot of the data of Fig. 5 to emphasize the background. The accidental coincidence rate was obtained from the ten channels on the right-hand side of this plot.

did not show any variation with time.

It should be noted that the statistical uncertainty in the result for B could be reduced by applying appropriate weightings to the values appearing in Table III. However, this assumes that the resolution and calibration of the β counter are known exactly. We believe that this approach is less reliable than the one that lumps all the data into a single β-energy group (95–783 keV), and our final values are based on this approach.

The older measurements of A have given -0.114 ± 0.019[9] and -0.09 ± 0.15.[15] A weighted average of these results and ours is $A = -0.115 \pm 0.008$. The latter value of A corresponds to $g_A = 1.26 \pm 0.02$; and if $G_S = G_T = 0$, this value of g_A in turn corresponds to $B = 0.99$.

The older measurements of B are 0.88 ± 0.15[9] and 0.96 ± 0.04.[16] A weighted average of these results and our new value (1.01 ± 0.05) is $B = 1.00 \pm 0.05$. This value of B can be used to suggest that (by the analysis described in Ref. 7) the maximum S or T contributions to the β interaction are less than 20%.

TABLE III. Comparisons between the values of A and B obtained with different selections of data.

Data used in calculation	Measured B[a]
All E_β: spin toward β counter	1.00 ± 0.06
: spin toward proton counter	1.03 ± 0.06
Both spin directions: $E_\beta = 95$–320 keV	0.93 ± 0.04
: $E_\beta = 320$–783 keV	1.11 ± 0.08
All	1.01 ± 0.04
	Measured A
Proton pulses: Large	0.116 ± 0.011
: Small	0.112 ± 0.015
: All	0.115 ± 0.009

[a] Uncertainties in polarization are not included.

These results favor the new measurement[7] of the neutron lifetime. The value of g_A is in excellent agreement with the theoretical calculation of Adler,[3,4] whose calculation involved contributions from off-mass-shell pion-proton cross sections and gave the result $g_A = 1.24 \pm 0.03$. It is also interesting that the discrepancy between the Goldberger-Treiman relation[17] and experiment is 15% if $g_A = 1.18$, but only 8% if $g_A = 1.26$.

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