Beta-Decay Asymmetry of the Neutron and g_A/g_V

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The β-decay asymmetry of the free neutron is measured by use of a beam of polarized neutrons and a long solenoidal β spectrometer with 4π solid angle for electron detection. The asymmetry parameter corrected for recoil and weak magnetism is $A_0 = -0.1146 \pm 0.0019$, implying $g_A/g_V = -1.262 \pm 0.005$ for the ratio of the axial-vector to the vector weak-coupling constants.

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From the β decay of the free neutron, $n \rightarrow p + e^- + \bar{\nu}_e$, one can obtain unique information on the weak interaction between quarks of the first generation. The structure of the charged weak current is believed to be described by the $V-A$ theory. Within this theory neutron decay is determined to good approximation (the allowed approximation) by momentum-independent vector and axial-vector weak coupling constants g_A and g_V. The constant g_V is presently most accurately determined from studies of nuclear $0^+ \rightarrow 0^+$ superallowed β decay.[1] The preservation of the vector coupling strength, despite the nuclear environment, is an important consequence of vector current conservation. The relatively small corrections, made necessary by electromagnetic isospin-symmetry breaking, are well enough understood[2] for uncertainties in them to be of no significant consequence for the analysis of our present results.

Axial-vector current conservation is known to be violated and g_A must be measured in free-neutron β decay. The ratio g_A/g_V has already been measured in a number of neutron-decay angular-correlation measurements and neutron-lifetime measurements.[3] There are, however, serious discrepancies and, in particular, several recent neutron-lifetime measurements disagree by as much as 7% while the individual experiments claim precisions of about 1%.[4] Meanwhile, the exact value of g_A/g_V has important consequences for the fundamental weak interaction as well as for astrophysics and cosmology,[5] and thus it is crucial to know it as well as possible. In this Letter we report on a sensitive measurement of the neutron-spin–electron-momentum angular correlation (the neutron β asymmetry) from which we obtain a precise value for g_A/g_V.

The decay probability per unit time for emission of electrons from a polarized neutron is given by

$$d\Gamma = [1 + (v/c) PA \cos\theta] d\Gamma(E), \qquad (1)$$

where v/c is the electron speed in units of the speed of light, θ is the emission angle relative to the neutron polarization P, A is the β asymmetry parameter which is nonzero because of parity nonconservation, and $d\Gamma(E)$ is the decay rate into a differential solid angle for unpolarized neutrons. In the allowed approximation the asymmetry parameter is

$$A_0 = -2\lambda(\lambda - 1)/(1 + 3\lambda^2), \qquad (2)$$

where $\lambda = |g_A/g_V|$ and time-reversal invariance with the usual phase convention is assumed.[6] In fact the true asymmetry parameter, A in Eq. (1), is energy dependent but its maximum deviation from A_0, due to recoil corrections and the effect of induced currents (weak magnetism is expected to be the only significant induced-current effect), is only 1%.

In our experiment we directly measure the β asymmetry from polarized neutrons by observing the difference in electron counting rates as a function of energy for the two neutron polarization states. The asymmetry parameter in the allowed approximation and ultimately g_A/g_V is extracted from fitting to the expected energy dependence of the counting rate asymmetry. Figure 1 shows the experimental apparatus schematically; the principal component is a superconducting solenoidal spectrometer (called PERKEO). The experiment is located in the guide hall of the Institut Laue-Langevin's 57-MW heavy-water reactor in Grenoble, France. Cold neutrons from a 23-K deuterium moderator, near the core, are transported to the experiment by a 120-m-long totally reflecting neutron guide. A supermirror polarizer[7] produces a beam with measured polarization >97%. A 1.7-m-long collimator with nine rectangular channels constructed from ^{6}LiF plates reduces the beam divergence. The beam cross section is 2.2×3.4 cm at the entrance of the spectrometer and it grows to only 3.2×5.0 cm at the exit. The

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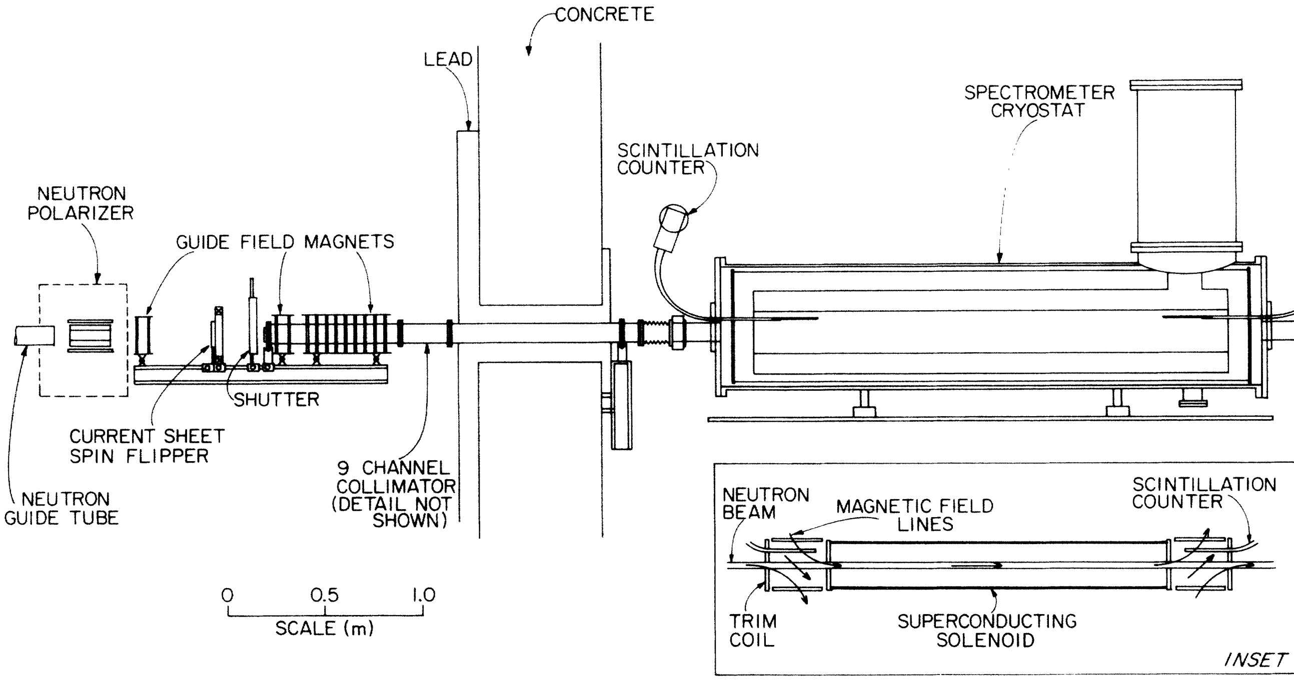

FIG. 1. Arrangement of the experiment. The inset shows details of the inner region of the superconducting solenoid.

integrated capture flux of the collimated beam is $\phi_c \approx 2\times 10^8$ neutrons/sec. The neutron polarization follows guide fields and inside the spectrometer the neutron polarization axis coincides with the beam direction and the solenoid axis. A current-sheet nonadiabatic spin flipper reverses the sense of the polarization at regular intervals.[8]

The PERKEO spectrometer is designed to enhance the counting rate from neutron decay by collecting decay electrons over a large region of the neutron beam. The main element is a 1.7-m-long, 20-cm-diam superconducting solenoid which produces a 1.5-T axial field. Electrons from neutron decay have kinetic energies <782 keV and they are constrained to helical paths with diameters less than 1 cm inside the spectrometer. Additional coils at each end of the solenoid bend the field lines causing the electrons to move away from the neutron beam and strike plastic scintillation counters, shown in Fig. 1. The spectrometer field decreases monotonically from the center of the solenoid to the detectors, insuring that electrons are not permanently trapped by the magnetic mirror effect. A correction in the asymmetry of about 10% for the magnetic mirror effect is necessary, however, because electrons are reflected for some trajectories if they are initially directed toward a region where the magnetic field increases.

The β detectors are made from $240\times 180\times 8$-mm-thick acrylic scintillator, Roehm GS 2003 (Rohaglas 2003) curved to conform to the cylindrical shape of the spectrometer. Each is coupled through light guides to two RCA 8850 photomultipliers operated in fast coincidence to reduce noise. The detector sensitivity corresponds to about 100 photoelectrons/MeV. The electronic thresholds are below the single photoelectron level and so the effective energy threshold is about 20 keV. One novel feature of the experiment is the ability to reconstruct electron backscatter events as coincidences between the two scintillation counters. The electron energy signal is derived from the sum of signals from both scintillators. The counter actually struck, that is, the initial direction of the decay electron, is recovered from timing information with hardwired logic. About 1% of the events have signals in both detectors.

During runs, the neutron polarization is reversed every 15 sec and data are collected under the control of a PDP 11/23 computer system interfaced through CAMAC. For background subtraction, runs with the neutron beam blocked after the polarizer by a ^{6}LiF shutter are alternated with data runs. The integral signal-to-noise ratio is approximately one-to-one with nearly all the background being below 200 keV. The spectrometer is energy calibrated periodically with several conversion-line sources (^{109}Cd, ^{113}Sn, and ^{207}Bi) deposited on thin backings and remotely inserted inside the solenoid.

The typical background-subtracted counting rate is 100 $\sec^{-1}$ per detector. Figure 2 is a background-subtracted electron energy spectrum from the upstream detector; both neutron polarizations have been added together producing an effectively "unpo-

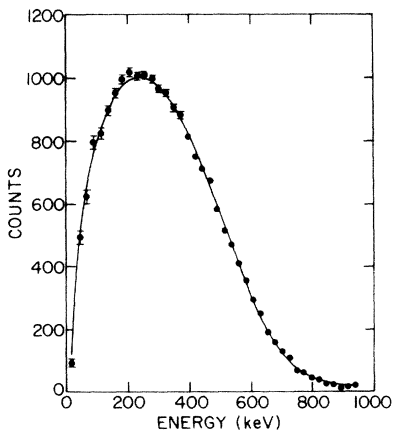

FIG. 2. β-decay energy spectrum from one run. Spectra for both polarization states are added and the solid curve is a fit to the resolution-corrected Fermi shape. The measured point at lowest energy is just at the threshold of the detectors.

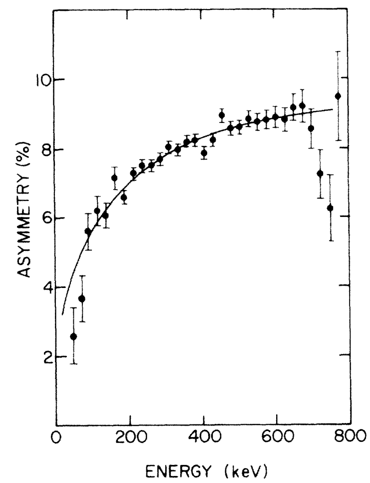

FIG. 3. Experimental β asymmetry as a function of β energy. The data for both detectors for all runs taken over a 150-h period are combined in the graph. The solid curve is the theoretical prediction after accounting for detector response.

larized'' β spectrum. The energy scale is derived from conversion-line calibrations and there is a small correction to the data points at low energies for measured detector nonlinearity. The data in Fig. 2 are fitted well by a function which represents the expected allowed spectral shape corrected for detector response. A Poisson resolution function with a low-energy cutoff is used to model the detector.

The downstream detector is not as well shielded from the polarizer and the collimator, and the background subtraction is not complete at low energies. Depending on experimental conditions (primarily shielding) that were changed during the run, occasionally the upstream detector spectrum also exhibited some unsubtracted background. Only the data above ~ 200 keV, where the background subtraction is good, are used to complete the final result. The systematic uncertainty in this procedure is accounted for in the final error.

To extract the β asymmetry parameter from the data we consider the following combination of experimental counting rates:

$$[N_{i\uparrow}(E)-N_{i\downarrow}(E)]/[N_{i\uparrow}(E)+N_{i\downarrow}(E)],$$

where the N's are experimental energy spectra for counter i and polarization state represented by the arrow. We expect from Eq. (1) that except for a slight complication from finite detector resolution this combination will have the form $\frac{1}{2}(v/c)PA(E)(1+f)S$. Here we have integrated over the 2π effective solid angle of each detector and we have included two correction factors: a factor f to account for imperfect neutron spin reversal, and a factor S to account for the magnetic-mirror effect is energy independent in the adiabatic approximation which is well satisfied by the experimental conditions.[9] Figure 3 shows the data combined in this way from 150 h of measurement. The data for both detectors are combined to enhance the statistics. Only the data from the upstream detector are included at low energies. The data are fitted well by the expected v/c dependence modified for finite resolution, and the slight energy dependence in A due to weak magnetism and nucleon recoil. The apparent systematic deviation at low energies in Fig. 3 may be due to incomplete background subtraction. The deviation counting rate is very small and the combination of counting rates plotted in Fig. 2 is very sensitive to background. These energy regions are avoided in the final determinations

The result of fitting the energy-dependent counting rate asymmetry with the amplitude as a free parameter determines the combination $\frac{1}{2}PA_0(1+f)S$. The data from each run and each detector are separately analyzed and the results are combined later. The neutron polarization P and the spin-flip probability are measured periodically in a separate experiment with a second supermirror polarizer and current-sheet spin reverser by a standard method.[10] We obtain $P=0.974(5)$ and $f=0.988(1)$ where the errors account for statistics and the systematic error of the method. Variations in P and f over the course of the run are negligible. The magnetic-mirror correction is calculated from the known magnetic field distribution and the neutron density position dependence. The procedure is straightforward and it is verified with measurements of electron reflections made with movable conversion-line sources. The correction differs slightly for the two detectors because of the divergence of the neutron beam. We find $S_1=0.883(5)$ and $S_2=0.887(5)$ for the two detectors. Combining the results[11] for both detectors from 32 runs amounting to 150 h of data collection we find $A_0 = -0.1146 \pm 0.0019$, implying $g_A/g_V = -1.262 \pm 0.005$. The errors are dominated by systematic uncertainties from background subtraction, detector response, and energy calibration. The sign of the asymmetry parameter is verified by our knowing the sense of the neutron polarization and the sign of the measured asymmetry. This result is consistent with a preliminary result,[12] $g_A/g_V = -1.270 \pm 0.009$, with the same device but without some recent improvements. Our result is more precise than, but in good agreement with, other values for g_A/g_V obtained from measurements of the neutron β-$\bar{\nu}$ correlation and previous measurements of the neutron β asymmetry.[3] With the value of g_V from $0^+ \rightarrow 0^+$ nuclear β decay[4] our result implies that the neutron lifetime is $\tau = 898 \pm 6$ sec, which falls between the two most precise direct lifetime measurements.

Within Cabibbo theory, the magnitude of g_A/g_V should coincide with the value $F+D$ derived from semileptonic hyperon decays. However, recent measurements[13] gave $F+D=1.18(2)$ from baryon decays other than that of the neutron (column 4 of Table 3 in Ref. 11).

In conclusion, we have built a β-decay spectrometer, PERKEO, which provides 4π detection of neutron-decay electrons and compensates for backscattering. In a low-background, high-rate experiment with polarized neutrons we have measured the β asymmetry as a function of energy, obtaining a precise value for g_A/g_V, and indirectly a new value for the neutron lifetime. The present experiment determines the neutron-decay lifetime (indirectly) more precisely than any of the direct lifetime measurements. The basic v/c dependence of the neutron β asymmetry is demonstrated for the first time.

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