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CORRELATION COEFFICIENTS IN POLARIZED NEUTRON DECAY - EXPERIMENTS WITH PERKEO*

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Measurements of the β-asymmetry in neutron β-decay combined with the results of studies of $0^+ \to 0^+$ superallowed nuclear β-decay is now the best way to determine the nucleon vector and axial vector coupling constants. High precision β-asymmetry experiments at the ILL using PERKEO have significantly reduced the error. Unlike the direct neutron lifetime measurements, which formerly claimed the smallest errors in g_A/g_V, the experiments that have measured the β-asymmetry are in good agreement.

The measurement of angular corrections in polarized neutron β-decay was pioneered in the late 50's and early 60's by Burgy, Krohn, Novey, Ringo and Telegdi[1] and by Clark and Robson.[2] In these experiments and those that have followed, no final state spins are observed. By detecting electrons and protons from polarized neutron decay these experiments measured A, the β-asymmetry parameter, B, the ν-asymmetry parameter, and D, a quantity that would indicate a time reversal non-invariant correlation between neutron spin and neutrino and electron momentum of the form $\vec{\sigma} \cdot \vec{p}_e \times \vec{p}_\nu$. Within the allowed approximation in the context of a V-A theory of the weak interaction, the correlation parameters are functions of only the vector and axial vector coupling constants, g_A and g_V. With the notation

$$g_A/g_V = \lambda\, e^{i\phi}\,, \quad \text{we have} \quad A \approx A_0 = \frac{-\,2\lambda(\lambda+\cos\phi)}{1+3\lambda^2}\,,$$

$$B \approx B_0 = \frac{2\lambda(\lambda-\cos\phi)}{1+3\lambda^2}\,, \qquad D \approx D_0 = \frac{2\lambda\,\sin\phi}{1+3\lambda^2}\,,$$

$$\text{and} \quad a \approx a_0 = \frac{1-\lambda^2}{1+3\lambda^2}\,.$$

Here a_0 is the allowed approximation for the β-ν correlation parameter, a, in unpolarized neutron decay. The neutron has structure and thus its β-decay properties depend on additional "induced" coupling constants. These additional form factors slightly modify the predictions of the allowed approximation. Neutron decay experiments are now nearly sensitive enough to detect deviations

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from the allowed approximation but presently recoil effects, induced current effects and radiative effects are included as corrections in determinations of the allowed form factors. Eventually, neutron decay experiments will measure the induced form factors providing tests of the conserved vector current hypothesis and the putting limits on second class currents, free from nuclear physics uncertainties.

Experiments indicate that $D \lesssim 10^{-3}$ and thus g_A and g_V are relatively real to a good approximation. However, the detection of a non-zero D arising from relatively complex g_A and g_V or from complex induced coupling constants remains an important issue for experiment investigation. Measurements of the parity violating correlations proportional to A and B as well as the parity conserving β-ν correlation parameter, a, have been useful for verifying the basic V-A nature of the weak force and as tools for determining the ratio of the vector and axial vector coupling constants.

The weak couplings g_A and g_V are fundamental constants that presently can only be determined from experiment. Vector current conservation preserves the quark vector coupling, and except for radiative corrections the neutron vector coupling is the same as the quark vector coupling. Indeed, current conservation also preserves the vector coupling strength in nuclei; g_V can be inferred from nuclear $0^+ \rightarrow 0^+$ superallowed β-decay after accounting for the isospin breaking of the electromagnetic interaction. However, the axial vector current is not conserved and g_A depends on the intricacies of quark interactions inside the nucleon; this manifestly nonperturbative phenomenon is not well understood. Within nuclei, the nucleon axial vector strength should be modified by the nuclear environment and since the process is not understood quantitatively, g_A can only be determined from free neutron β-decay. Apart from their importance in nuclear and particle physics the nucleon weak couplings are critical experimental inputs to theories of astrophysics and cosmology and a great deal of effort goes into determining g_A and g_V experimentally. It turns out that g_A/g_V is close to -1.25 and thus B is rather insensitive to the exact value while A and a are very sensitive. In the past, neutron lifetime measurements have claimed the greatest precision for determining g_A/g_V. However, several of the neutron lifetime measurements are inconsistent and consequently there is a large uncertainty because it is impossible to choose between experiments. As we shall see, the situation has changed and now β-asymmetry measurements provide the most precise g_A/g_V. Except for the most recent experiments with the electron spectrometer PERKEO to be discussed below, all β-asymmetry experiments have followed the general scheme of the pioneering works.

Figure 1 illustrates the apparatus of Clark and Robson.[2] Polarized neutrons were obtained by Bragg reflection off a ferromagnetic crystal of Co-Fe. Other versions of the experiment used small angle reflection from magnetized Co-Fe mirrors to produce polarized neutrons. The β-asymmetry can be measured by simply detecting the electron from polarized neutron decay but to reduce the background it was necessary for Clark and Robson to detect recoil protons in coincidence. In this type of experiment the β-asymmetry is derived from the variation in the β-proton coincidence rate with neutron polarization. Table I shows some important characteristics of β-asymmetry experiments. The early experimenters suffered with the low count rates resulting from the low polarized neutrons fluxes then available and because the experiments had small

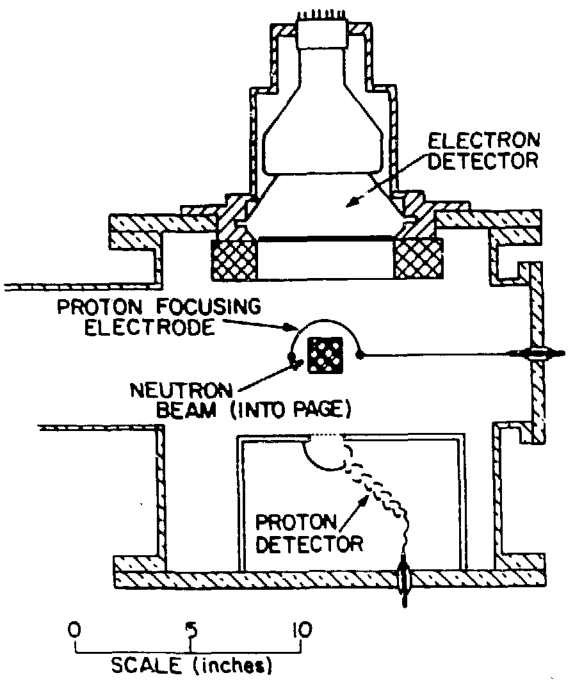

Fig. 1. Experimental arrangement of Clark and Robson.[2] Other β-asymmetry experiments employing coincident electron and proton detection were similar in concept.

source volumes and low detection efficiencies. The earlier experiments were limited both by statistics and systematic error. One type of systematic error resulted from a tendency for biased proton detection efficiences as a consequence of the large ν-asymmetry coefficient (B ≈ 1).

The newest β-asymmetry experiment benefits from several recent technical advances. The experiment employs the PERKEO β-decay spectrometer at the

Table I. Characteristics and Results of β-asymmetry Measurements.

Year	Reference	Polarization (%)	Typical Count Rate (sec^{-1})	Asymmetry	g_A/g_V
1960	Burgy et al.[1]	84±7	0.015	-0.114(19)	-1.257(50)†
1961	Clark & Robson[2]	89±5	-	-0.090(50)	-1.20(12)†
1969	Christensen et al.[3]	87±3	0.013	-0.115(9)	-1.260(23)†
1971	Erozolimskii et al.[4]	77±2	0.055	-0.120(10)	-1.273(27)†
1975	Krohn & Ringo[5]	79±1.5	0.117	-0.111(8)	-1.249(22)†
1976	Erozolimskii et al.[4]	73.3±2	0.106	-0.112(5)	-1.257(14)†
1984	Bopp et al.[6]	96.7±0.7	300	-0.118(3)*	-1.270(9)
1985	Bopp et al.[6]	97.4±0.5	300	-0.1146(19)*	-1.262(5)

*The asymmetries in these experiments are corrected to correspond to the β-asymmetry in the allowed approximation (A_0).

†The value of g_A/g_V is obtained by correcting A for induced effects and recoil over the reported energy range by the method described in Ref. 7.

Institute Laue-Langevin's 57 MW heavy water reactor at Grenoble, France. PERKEO is located at the end of a cold neutron guide about 120 m from the reactor. Unlike previous experiments, the detectors sit in a low background environment far from the reactor. A supermirror polarizer, another development of the ILL, produces an intense beam with measured polarization > 97%. To further enhance the count rate, the new experiment has 4π detection efficiency over a large region of the neutron beam. Consequently this is the first β-asymmetry measurement accomplished without the need for coincidence proton counting and the count rate is more than three orders of magnitude higher any of the previous experiments.

Figure 2 shows the experimental apparatus. The main component of the experiment is a 1.7 m long 20 cm diameter superconducting solenoid which produces a 15 kgauss magnetic field. After the beam passes the polarizer, guide fields rotate the neutron polarization to be along the axis of the solenoid. The polarization is reversed with a non-adiabatic current sheet spin flipper. A 1.7 m long 9-channel collimator constructed of ^{6}LiF plates produces a neutron beam with a 3x5 cm cross section and a very small divergence. The collimated polarized beam has a capture-flux of 8×10^9 sec^{-1}. Electrons from neutron decay have kinetic energies < 782 keV and they are constrained to move in helical paths with diameters less than 1 cm inside the solenoid. Coils at the ends of the solenoid distort the solenoidal field lines causing electron trajectories to intersect plastic scintillator detectors positioned above the neutron beam. Each scintillator is coupled through light guides to two RCA 8850 photomultiplers operated in coincidence to reduce noise. The detector sensitivity is about 100 photoelectrons/MeV. One novel feature of the experiment is the ability to reconstruct electron backscatter events as coincidences between the two scintillation counters. The electron energy is derived from the sum of both scintillator signals and the detector hit first is determined by timing. About 1% of the events are coincidences. The detectors are easily calibrated with respect to energy with remotely inserting conversion line sources (^{109}Cd, ^{113}Sn and ^{207}Bi) on thin backings. The typical background subtracted neutron decay count rate is about 150 sec^{-1} per detector.

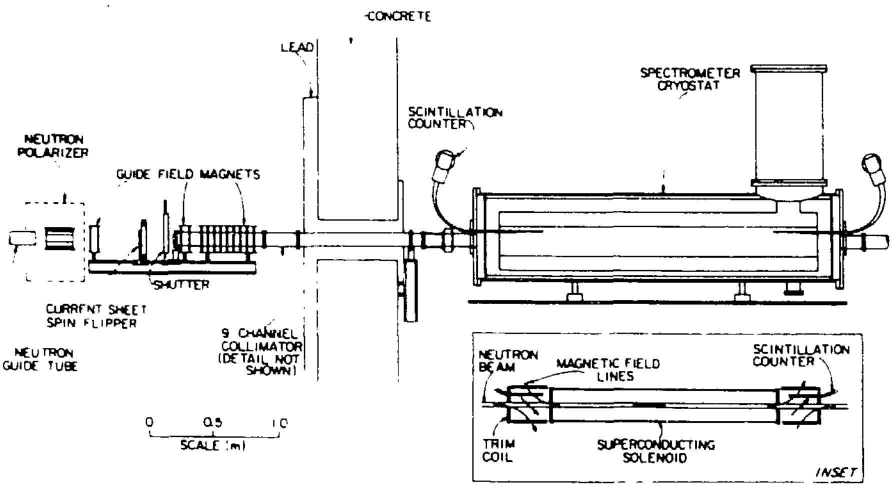

Fig. 2. Eperimental arrangement of PERKEO. The inset shows details of the inner region of the superconducting solenoid.

The experiment measures the β-asymmetry in the simplest way by measuring the count rate asymmetry as a function of β-energy for the two neutron polarization states. To extract the β-asymmetry parameter from the data one considers the following combination of experiment count rates:

$$(N_i^{\uparrow}(E) - N_i^{\downarrow}(E))/(N_i^{\uparrow}(E) + N_i^{\downarrow}(E)) ,$$

where the N's are the experimental energy spectra for counter i and polarization state represented by the arrow. Except for a slight complication from finite detector resolution this combination will have the form $\frac{1}{2}\frac{v}{c}PA(E)(1+f)S$. Two correction factors are included: a factor f to account for imperfect spin reversal, and a factor S to account for the magnetic mirror effect. The magnetic field in the spectrometer decreases monotonically from the center of the solenoid to the detectors and thus electrons are never permanently trapped. Nevertheless, a correction in the asymmetry for the magnetic mirror effect of about 10% is necessary to account for events in which the electron is initially directed to a region of increasing magnetic field.

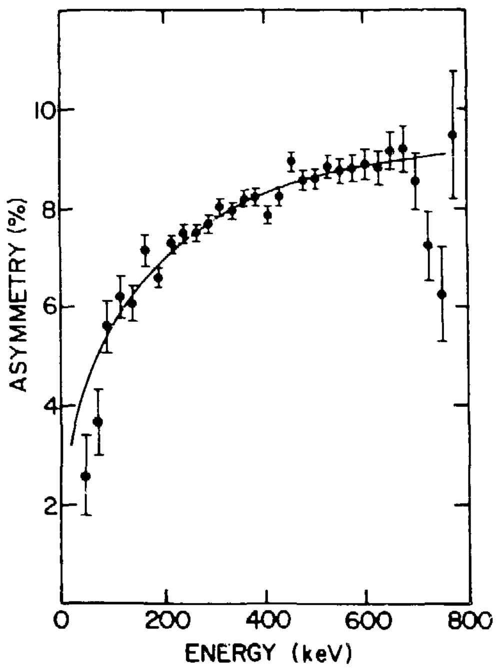

Fig. 3. Experimental β-asymmetry as a function of β-energy from 150 hours of data taken with PERKEO.

Figure 3 is the experimental asymmetry as a function of energy for 150 hours of running. The data is well fit by a function which accounts for the basic v/c energy dependence corrected for weak magnetism, recoil and detector resolution. After accounting for these effects a one-parameter fit determines the combination $\frac{1}{2}PA_0(1+f)S$. The neutron polarization, P, and the spin flip probability, f, is measured periodically during the run. The magnetic mirror correction, S, is straightforward to calculate and the calculation is verified with measurements made with movable conversion line sources.

In the most recent run of the experiment the determined polarization and spin probability are P = (97.4±0.5)% and f = (98.8±0.1)%. The correction for the magnetic mirror effect is slightly different for the two detectors because of the divergence of the neutron beam: S_1 = (88.3±0.5)% and S_2 = (88.7±0.5)%. The data for 150 hours of running gives A_0 = -0.1146(19), implying g_A/g_V = -1.262(5). The error is dominated by systematic uncertainties in the polarization measurement, the background subtraction procedure, the detector response and the energy calibration. The sign of the asymmetry parameter is verified by knowing the sense of the neutron polarization and the sign of the measured asymmetry.

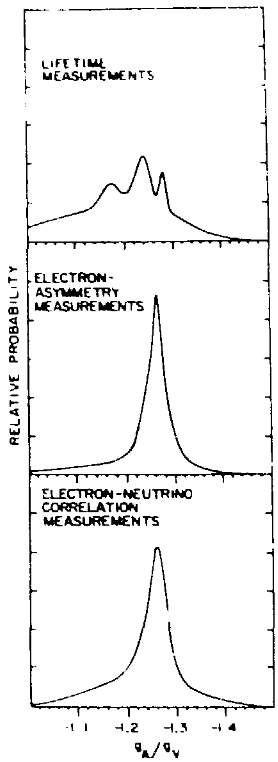

Fig. 4. Ideograms of experiments that determine g_A/g_V. The three ideograms have equal areas.

This value of g_A/g_V can be combined with the value of g_V from superallowed nuclear β-decay to give a prediction for the neutron halflife: $\tau_{1/2} = 622(4)$ sec. This inferred halflife is more precise than any so far obtained from a direct halflife measurement. The value of g_A/g_V determined with PERKEO agrees well with previous correlation measurements.[8]

Figure 4 shows ideograms of the three types of experiments which measure g_A/g_V. It is evident that the lifetime measurements are inconsistent but that the two types of correlation measurements are in good agreement. Indeed the nine lifetime experiments reported since 1951 give a very poor reduced chisquare of about 5. It is interesting to note, however, that the weighted average of g_A/g_V from lifetimes is -1.257 ± 0.005 in good agreement with $g_A/g_V = -1.256\pm0.015$ from the three best e-ν-measurements and with $g_A/g_V = -1.262\pm0.004$ from the eight β-asymmetry measurements done so far.

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