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The β -decay asymmetry of the free neutron

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MASTER

Resumé - La désintégration β des neutrons polarisés a été étudiée à l'aide du nouveau spectromètre supraconducteur PERKEO à l'ILL. La dépendance en énergie de l'asymétrie β a été mesurée pour la première fois. De l'asymétrie β mesurée on obtient une nouvelle valeur pour le rapport g_A/g_V des coefficients du couplage faible.

Abstract - The β -decay of polarized neutrons has been studied with the new superconducting spectrometer PERKEO at the ILL. The energy dependence of the β -decay asymmetry has been measured for the first time. From the measured β -asymmetry parameter we obtain a new value for the ratio of weak coupling constants g_A/g_V .

We report the first results obtained with the superconducting β -spectrometer PERKEO at ILL. PERKEO measures neutron decay β -spectra with a 4π solid angle over a large volume of a cold neutron beam. The count rates from polarized neutron decay achieved with this instrument are several orders of magnitude higher than any previous experiment. In the present experiment, serious sources of systematic error, arising from β -backscattering and poorly defined source volume and detector solid angle, are largely eliminated. In the first experiment with PERKEO we have studied the size and β -energy dependence of the β -decay asymmetry of the neutron.

The angular distribution of the electron emitted in polarized neutron decay is given by

$$W(E, \theta) dE d\Omega = F(E) \left(1 + \frac{v}{c} PA \cos\theta\right) dE d\Omega. \quad (1)$$

The Fermi function, $F(E)$, is a function of β kinetic energy, approximately given by the expression,

$$F(E) = (E_0 - E)^2 (E + mc^2) \sqrt{E(E + 2mc^2)}. \quad (2)$$

Here E_0 is the maximum value of E , v/c is the electron speed in units of the speed of light, θ is the emission angle relative to the neutron polarization P , and A is the β -asymmetry parameter which is nonzero because of parity violation. Except for small corrections from induced currents and radiative corrections, A is predicted in the V-A theory to depend solely on the ratio of the axial-vector and vector weak coupling constants, g_A/g_V . With $\lambda = |g_A/g_V|$, we have

$$A = -2\lambda \frac{\lambda - 1}{1 + 3\lambda^2}. \quad (3)$$

Since λ turns out to be near unity measuring A is in general a good way to determine λ relative to other neutron decay correlations or measurements of the

neutron lifetime. We note that subject to the assumption that the vector current is conserved g_V is reliably determined from nuclear β -decay data but direct knowledge of g_A comes solely from neutron decay. The precise values of g_A and g_V are important to weak interaction phenomenology and should be determined as well as possible. Recently the neutron weak form factors have been recognized as an important ingredient in cosmological arguments.

PERKEO is shown schematically in Fig. 1. The principal component is a 1.7 m long 20 cm diameter superconducting solenoid which produces a ≈ 1.5 Tesla field along the direction of the neutron beam. Electrons from neutrons decaying inside the spectrometer move in helical paths $\lesssim 1$ cm in diameter with axis along magnetic field lines. Four trim coils at either end distort field lines causing electron trajectories to bend away from the neutron beam. The electron trajectories are finally intercepted by plastic scintillation counters located at each end of the spectrometer. The magnetic field strength decreases continuously towards both ends of the spectrometer, so no electrons can be magnetically trapped. The electron flight times between the detectors is effectively within the range $7 \text{ ns} \lesssim t \lesssim 300 \text{ ns}$.

Fig. 1. Schematic layout of PERKEO.

Each scintillator is coupled to two photomultipliers and coincidence signals with thresholds below the single photoelectron level are required to reduce noise. The detectors are calibrated with various conversion line sources. Fig. 2 shows the typical response. The observed resolution corresponds to ≈ 160 photoelectrons/MeV.

The scintillators are large enough so that the total detection solid angle is 4π -str within the spectrometer. An electron back-scattered from a detector is either reflected back by the magnetic mirror effect or it moves along a field line to the other detector. Since both detector signals are summed the total electron energy is recorded. About 1% of the neutron decay events have the measured electron energy shared in the two detectors. The detector hit first and thus the initial electron velocity component along the spectrometer axis is identified by the timing of the detected signals.

PERKEO is located at the polarized neutron experimental station PN7 at ILL. The total capture flux into the spectrometer

Fig. 2. Detector response to various conversion line sources.

from the PN7 supermirror polarizer is $(8 \pm 3) \times 10^9 \text{ sec}^{-1}$. The beam is collimated both horizontally and vertically by a 1.8 m long 3×3 channel collimator made entirely from sintered ^6LiF . The beam cross section thus defined is $3.8 \times 5.6 \text{ cm}^2$ at the exit of the spectrometer. No evidence for a halo on the neutron beam is observed at the 10^{-5} level. During measurements of the β -asymmetry neutrons are longitudinally polarized and the polarization is switched every 5 sec with a current sheet spin flipper.

Figure 3 is the background subtracted unpolarized β -spectrum obtained by summing the spectra taken for equal times from each detector and both neutron polarizations. The solid curve through the data is a fit to the expected shape including detector resolution; only data above 250 keV is used in the fit. The unsubtracted background at low energies, evident in Fig. 3, is beam related. Improvements planned for future runs are expected to essentially eliminate this background. The total neutron decay count rate is 165 sec^{-1} .

We define the experimental asymmetry as

$$A_\beta = \frac{N_1^\uparrow - N_1^\downarrow}{N_1^\uparrow + N_1^\downarrow} - \frac{N_2^\uparrow - N_2^\downarrow}{N_2^\uparrow + N_2^\downarrow} \quad (4)$$

where the N's are energy spectra for equal times; 1 and 2 refer to the detector, $\uparrow$ and $\downarrow$ to the polarization.

From (1) we have

$$A_\beta = \frac{1}{2} (1 + f) \frac{v}{c} \text{PSA} [1 + a(E)]. \quad (5)$$

The factor of $1/2$ is from averaging over the detector solid angle; f is the spin flip reversal efficiency; and S corrects for magnetic mirror reflections in the inhomogeneous fields at the end of the spectrometer. S is reliably calculated from the known field distribution, we obtain $S = 0.890(15)$. The energy dependence of A_β is dominated by the factor v/c but the additional factor $1 + a(E)$ accounts for a small but not negligible effect from weak magnetism and radiative corrections (see for example reference 1).

The unsubtracted background evident in Fig. 3 obviously distorts A_β at low energies. For the present analysis we fit the spectra for $N_1^\uparrow + N_1^\downarrow$ to the resolution corrected Fermi shape using only the higher energy data and use the determined curve instead of the data as the denominators in Eq. 4. Presumably this procedure will not be necessary in future experiments. Figure 4 is the resulting graph of A_β from one run determined by the above procedure. The data are in accord with the energy dependence expected from the v/c factor.

The neutron polarization and spin flip efficiency are determined to be $P = 96.7(7)\%$ and $f = 99.8(3)\%$ from measurements with a second supermirror and spin flipper and studies of the time of flight polarization spectrum of the neutron beam.

Fig. 3. The β -decay energy spectrum from one run. The solid curve is a fit to the resolution corrected Fermi shape. The fit includes only those data above 250 keV.

To determine A from A_β we use only the data above 250 keV. We obtain the preliminary value $A = -0.118(3)$ which is corrected for weak magnetism and radiative effects. The individual corrections and sources of errors are listed in Table 2. From Eq. 3 we obtain the preliminary result $\lambda = 1.27(1)$. The solid curve in Fig. 4 is the prediction for the experimental A_β with $\lambda = 1.27$; the dashed curve is the corresponding prediction for $\lambda = 1.24$ which is the value suggested in Ref. 9.

Table 3 lists given values of λ determined by other recent experiments. Our experiment is the first to measure the β -asymmetry without counting proton recoils in coincidence and it is the first to verify the v/c dependence of the experimental asymmetry.

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Fig. 4. Experimental β -ray asymmetry from one run as a function of β -energy. The curves are expectations for two values of λ .

TABLE 1. Count rates and polarizations in various polarized neutron decay experiments.

Year	Ref.	β -counts/hour N	n-polarization P	Relative Quality Factor $Q \propto P^2 N$
1970	2	100	0.870(30)	1
1971	3	200	0.770(20)	1.6
1975	4	420	0.790(15)	3.5
1979	5	420	0.733(20)	3.0
1982	This work	600,000	0.967(7)	7,500

TABLE 2. Corrections applied in determining A.

Correction due to:	Correction	Error
n-polarization P	+ 0.0040	± 0.0007
n-flip efficiency f	+ 0.0001	± 0.0002
electron magn. refl. S	+ 0.0127	± 0.0020
β -detector:		
energy calibration	--	± 0.0010
energy resolution	+ 0.0003	± 0.0001
residual background	+ 0.0008	± 0.0005
radiative corrections	- 0.0006	± 0.0002
weak magnetism (CVC)	- 0.0012	--
total correction	+ 0.0161	± 0.0024
statistical error		± 0.0020
total error	± 0.0031	
preliminary result -0.1178 ± 0.003		

TABLE 3. Summary of recent λ -measurements.

Year	Ref.	Quantity Measured	λ
1972	6	$T_{1/2} = 636.6(9.6)$	1.245(11)
1978	7	$T_{1/2} = 607.8(5.4)$	1.280 (7)
1980	8	$T_{1/2} = 649(12)$	1.230(14)
1982	9	PDG recomm. value $T_{1/2} = 641(8)$	1.239 (9)
1978	10	$a = -0.1017(51)$	1.259(17)
1975	4	$A = -0.113(6)$	1.254(15)
1979	5	$A = -0.114(5)$	1.257(12)
1983	This work (preliminary)	$A = -0.118(3)$	1.270 (9)
1983	11	Various hyperon decay parameters + Cabbibo hypothesis	1.233(16)

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