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Measurement of the Neutrino Asymmetry Parameter *B* in Neutron Decay

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A new measurement of the neutrino asymmetry parameter *B* in neutron decay, the angular correlation between neutron spin and antineutrino momentum, is presented. The result, $B = 0.9802(50)$, confirms earlier measurements but features considerably smaller corrections. It agrees with the standard model expectation and permits updated tests on "new physics" in neutron decay.

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Assuming only Lorentz invariance, the decay probability for polarized neutrons is given by [1]

$$d\omega \propto K dE d\Omega_e d\Omega_\nu \Big(1 + a\frac{\boldsymbol{p}_e \boldsymbol{p}_\nu}{EE_\nu} + b\frac{m_e}{E}$$
$$+ \langle \boldsymbol{s}_n \rangle \Big[A\frac{\boldsymbol{p}_e}{E} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{EE_\nu} \Big]\Big). \quad (1)$$

$\boldsymbol{p}_e$, $\boldsymbol{p}_\nu$, E, E_ν are momentum and energy of electron and antineutrino (in the following called neutrino), respectively, m_e is the electron mass, $\langle \boldsymbol{s}_n \rangle$ is the neutron spin polarization, and the Ω_i denote solid angles. The parameters *a*, *A*, *B*, and *D* are angular correlation coefficients: *a* is the correlation between the momenta of electron and neutrino. The parity violating parameters *A* and *B* for electron and neutrino asymmetry correlate the neutron spin with the momentum of electron and neutrino, respectively. The subject of this Letter is a precise measurement of *B*.

The factor *K* and the correlation coefficients are related to the couplings of the theory. Within the standard model of particle physics (SM), *b* vanishes and *D* is much smaller than the present experimental limit. $K = G_F^2 |V_{ud}|^2 F(E) \times (g_V^2 + 3g_A^2)$, with Fermi-constant G_F, quark mixing matrix element V_{ud}, phase space factor $F(E)$, and vector and axial-vector coupling constants g_V and g_A. All correlation coefficients are functions of $\lambda = g_A/g_V$, where g_A and g_V are assumed to be real, e.g.,

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

Small higher order corrections must be considered additionally. The structure of the weak interaction ($V - A$ in the SM) is not predicted by theory but has to be determined experimentally. Because of its sensitivity to the neutrino helicity the neutrino asymmetry parameter *B* is an important input parameter for this purpose: Precise measurements of *B* [2–4] can be used to derive limits on hypothetical right-handed current ($V + A$) contributions to β-decay [5–7] (mediated by new heavy charged bosons

W_R). These can be compared to other indirect measurements in muon [8] and nuclear β-decay [9] as well as to collider attempts to directly produce the W_R [10] (cf. also [11]). When interpreted in general left-right symmetric (LRS) models beyond manifest LRS theory, information from all these experiments (direct, muon, and β-decay) are complementary and necessary to obtain limits [9].

A deviation from Eq. (2) is a signal for new physics not described within the standard model and may be due to admixtures of right-handed currents, or due to anomalous (scalar, tensor) couplings possibly caused by exotic models like leptoquark exchange [12]. A recent review on this topic can be found in [13]. Neutron decay, involving all particles of the first generation, is well suited to study the structure of the weak interaction [14] since theoretical corrections are small and well calculable as they do not depend on nuclear structure [15–17].

In order to measure the neutrino asymmetry parameter *B*, the electron spectrometer PERKEO II [18] was installed at the cold neutron beam position PF1B [19] at the High Flux Reactor of the Institut Laue-Langevin (ILL), Grenoble. A cold neutron beam with a thermal equivalent flux of $1.3 \times 10^{10} n$ cm^{-2} s^{-1} was transversally spin polarized in a system of two supermirror polarizers in the new X-SM geometry [20]. A radio frequency (rf) spin flipper [21] allowed us to reverse the spin direction. Polarization *P* and spin flipper efficiency *F*, formerly sources of large corrections and uncertainties, were determined to $P = 0.997(1)$ and $F = 1.000(1)$ leading to a 0.30(14)% correction on *B*. *P* and *F* were measured as a function of the neutron wavelength by a time-of-flight method. A second rf flipper and two supermirror analyzers in the geometry of [20] were used to determine *F* and to scan *P*. For the precise measurement of the absolute beam polarization, several opaque polarized ³He cells [22,23] were employed. Both, *P* and *F* were uniform over the full neutron beam cross section for all wavelengths. The flipping ratio, a measure for *PF*, was monitored regularly and stayed constant during beam time.

Behind the polarizers, a neutron shutter was installed for background measurements in the electron detectors. It was made of enriched ^{6}LiF, as were the neutron beam collimation orifices and the beam stop at the end of the installation, since generation of γ-radiation and fast neutrons in ^{6}LiF is suppressed by 10^4 [24]. Additional shielding was employed to reduce the remaining background.

A certain fraction of neutrons decayed within the decay volume centered in the spectrometer. Its main part is a pair of superconducting coils in split pair configuration, generating a magnetic field with a maximum of 1.03 T perpendicular to the neutron beam (Fig. 1). The neutron spin aligns with the field that therefore separates the full solid angle in two hemispheres: One in and one against neutron spin direction. It guides the charged decay products onto the two detectors installed next to the beam, realizing a $2 \times 2\pi$ detector where no solid angle corrections have to be applied. Systematic effects related to the spectrometer design are described below. A detailed description of a previous experiment can be found in [4].

The magnetic field B' decreases towards the detectors. This causes an increase of the parallel momentum component of the particles leading to reduced electron backscattering. This is further reduced by the "magnetic mirror effect": Electrons scattered out of the detector may be reflected at the increasing B' and still detected in the correct hemisphere. Backscattering is recognized via its delayed signal in the second detector. The full energy of the decay electron is reconstructed. The fraction of events assigned to the wrong detector is smaller than 0.2%, a neglectable systematic effect ($<10^{-4}$) if the region of interest is chosen above a β-energy of 240 keV [25].

Since the neutrino cannot be measured directly, electron and proton were detected in coincidence to reconstruct the
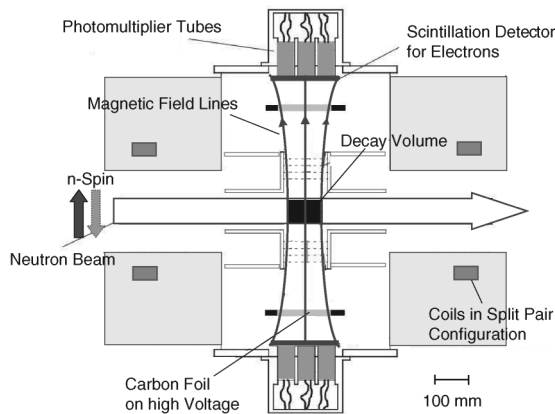

FIG. 1.   The spectrometer PERKEO II: Polarized neutrons pass the setup, the magnetic field divides the full solid angle into two hemispheres—in and against spin direction—and guides the decay products onto the detectors. The low energetic protons are accelerated onto a thin carbon foil on negative potential, where they generate secondary electrons that can be detected by the scintillators.

neutrino. Most sensitive to B is the case when electron and proton are emitted into the same hemisphere relative to the neutron spin—momentum conservation then restricts the neutrino to the opposite direction. The other case, where electron and proton are emitted into different hemispheres, is kinematically favored but less sensitive to B since the neutrino direction is less constrained [26]. As it depends strongly on detector calibration, this case was only used for cross checks of the result obtained for the first case.

Electrons ($E_{max} = 782$ keV) are detected by 190×130 mm^2 plastic scintillators with photomultiplier readout. The protons having much lower energies ($E_{max}^p = 780$ eV) are accelerated onto a thin carbon foil (15–30 μg cm^{-2}, coated with MgO) on negative potential ($V = -18$ kV). Whereas the electrons pass the foil almost unperturbed, the heavy protons have enough ionization power to release one or several secondary electrons from the foil [27]. These are detected in the scintillator, where also the proton time of flight is registered. No precise energy information on the proton is obtained with this method. Proton detection does not depend on the initial proton energy and the angles of incidence occurring in this setup as was experimentally verified.

The measured signature is the experimental neutrino asymmetry defined by

$$B_{exp}(E) = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}, \quad (3)$$

where $N^{ij}(E)$ is the number of coincident events with electron kinetic energy E. The first (second) sign indicates whether the electron (proton) was emitted in ($+$) or against ($-$) neutron spin direction. Equation (3) is related to the neutrino asymmetry parameter B by integrating Eq. (1) over the hemisphere [16,26]

$$B_{exp}(E) = \frac{4P}{3} \begin{cases} \frac{A\beta(2r-3)+B(3-r^2)}{8-4r+a\beta(r^2-2)} & [r < 1] \\ \frac{-A\beta+2Br}{4r-a\beta} & [r \geq 1]. \end{cases} \quad (4)$$

The definition is separated into two regions by the energy dependent parameter $r = \beta(E + m_e)/(E_{max} - E)$ which is unity at $E = 236$ keV. $\beta = v/c$. Equation (4) is very sensitive to the coefficient B but also depends slightly on the correlations a and A whose experimental uncertainties have to be considered.

Detector calibration was performed regularly and two-dimensional detector scans were carried out to correct for spatial detector characteristics. Due to the flat spectral shape of $B_{exp}(E)$ detector calibration imposes only a tiny uncertainty of 0.02% on B.

At low electron energies, there is background related to the high voltage (HV) applied on the carbon foils. Above 230–240 keV, however, the measured electron spectra, i.e. $N^{++}(E)$ and $N^{--}(E)$, can be well described by their theoretical expressions, where all fits have only one free parameter, a normalizing factor. An upper limit on remain-

ing background contributions in the fit region was deter-
mined from the fit residuals. At lower energies, a satisfac-
tory description is impossible due to background, a
nonlinear energy calibration, and backscattered electrons
assigned to the wrong detector [28].

All corrections due to the spectrometer design have been
obtained from Monte Carlo simulations. The "edge effect"
accounts for the loss of charged particles due to the finite
length of the decay volume that was defined by thick
aluminum baffles. "Grid effect": Four layers of grids
made of AlSi-wires (10 μm and 25 μm) were used to
prevent the HV applied to the detector foils to reach into
the decay volume. Different methods (finite elements,
boundary elements) showed that the absolute electric po-
tential in the decay volume is at least 1 order of magnitude
below a value that would cause systematic effects at the
present level of experimental precision. However, elec-
trons and protons may be absorbed or scattered by the
grids. This "grid effect" was obtained using the program
PENELOPE [29] to simulate the electron trajectories in the
wires. Protons hitting the wires were assumed to be ab-
sorbed. The potential barrier for electrons to reach the
scintillator can be neglected since all electrons with $E >$
84 keV will certainly pass it regardless of their initial
emission direction.

Charged particles moving in an increasing magnetic
field B' may be reflected as $p_\perp^2/B'$ is an adiabatic invariant,
where $p_\perp$ is the momentum component perpendicular to
the field lines. This gives rise to the "magnetic mirror
effect" since a certain fraction of decay products was
emitted towards the field maximum due to the finite neu-
tron beam width. An asymmetric setup, i.e., a displacement
Δ between neutron beam and magnetic field maximum,
may cause an additional, possibly large effect on B.
Therefore Δ was measured directly and was additionally
determined from data in two independent ways to correct
for the effect: It was obtained from a χ^2-minimization of
fits to the difference spectrum $D(E) = N^{--}(E) - N^{++}(E)$
that has the highest sensitivity on Δ at high electron
energies E. Δ was also determined from the relative dif-
ference of the electron asymmetry parameters A measured
without ep coincidence with the two detectors. This was
possible due to the symmetric setup and since beam related
background, i.e., background generated in the collima-
tion system that cannot be measured separately, is small
($<10^{-4}$) and also symmetric in a region $E > 350$ keV [30].
The resulting values for Δ do virtually not depend on B nor
on other systematic effects. The associated error of 0.32%
constitutes the largest systematic uncertainty of the
measurement.

$F(E)$ in Eq. (1) has already been corrected for Coulomb
interactions $F_C(E)$, proton recoil $R(E)$, and outer radiative
corrections $\delta_R(E)$, and reads

$$F(E) = F'(E)[1 + \delta_R(E)][1 + R(E)]F_C(E), \quad (5)$$

where $F'(E)$ is the uncorrected phase space factor. The
expressions for $\delta_R(E)$ and $R(E)$ were taken from [15,31],
respectively. The recoil and order-α corrections to B are of
order 0.01% [16].

The proton coincidence window W_1 was restricted to
40 μs causing a small correction of $-0.05(3)$% to account
for slower protons. Accidental coincidences were directly
measured with a delayed coincidence technique in a de-
layed window W_2 from 42–82 μm after the initial trigger.
In order to avoid suppression of protons by accidental
coincidences or background, or suppression of accidental
coincidences by preceding signals, up to 32 stops were
detected in both detectors. Only events with exactly one
stop in the respective window were considered in the
analysis since multiple stops are mostly due to background.
Events with a stop in W_1 and a second ("accidental") stop
in W_2 were included in the analysis.

However, this "1 stop" condition causes an overestima-
tion of accidental coincidences since the stop-signal com-
bination "proton and accidental signal" in W_1 is removed
from the data set, whereas a similar combination does not
occur in W_2. The available information on all stops allowed
to determine the necessary correction directly from the
data.

At high electron energies E, the fit region is limited as
the uncertainty related to the displacement Δ between
neutron beam and magnetic field increases with E. At the
low energy side, the fit region is limited by the effects
mentioned above: Background, nonlinear detector re-
sponse, and wrongly assigned backscatter events. The
region was chosen from 250–455 keV. The final asymme-
try parameter B is independent of this choice as the fit
results agree within $\pm 0.3\sigma_{\text{stat}}$ for intervals between 235
and 620 keV (fig. 4.48 in [28]).

Figure 2 shows the fit of B_{exp}, Eq. (4), to all data of
detector 2 (proton efficiency of about 17%). It yields the
neutrino asymmetry parameter $B_2 = 0.9798(36)_{\text{stat}}(36)_{\text{syst}}$.
The result of detector 1, $B_1 = 0.9845(120)_{\text{stat}}(36)_{\text{syst}}$, is
limited by statistics due to a smaller proton efficiency.
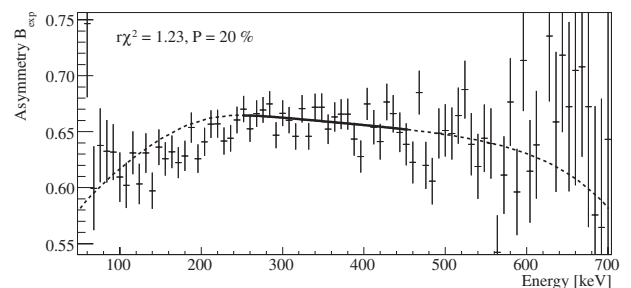This was caused by an inferior foil coating and higher

FIG. 2. Fit of B_{exp} to all detector 2 data. The solid curve
indicates the fit region. The result does not depend on this region.
However, the overall uncertainty increases if the fit is extended
to higher energies due to the magnetic mirror effect.

TABLE I.   Neutrino asymmetry B: corrections and errors.

Effect [%]	Detector 1		Detector 2	
	Corr.	Err.	Corr.	Err.
Polarization	+0.30	0.10	+0.30	0.10
Flip Efficiency		0.10		0.10
Data Set: *Statistics*		1.22		0.36
Proton Window	−0.05	0.03	−0.05	0.03
1 Stop Condition	−0.24	0.06	−0.13	0.03
Background		0.10		0.08
Detector Calibration		0.02		0.02
Spectrometer: *Edge Effect*	−0.16	0.05	−0.16	0.05
Grid Effect	+0.03	0.05	+0.03	0.05
Mirror Effect	+0.44	0.05	+0.44	0.05
Displacement Δ	−0.10	0.32	+0.10	0.32
Correlations *A, a*		0.07		0.07
Sum	+0.22	1.28	+0.53	0.52

HV background that could not be further suppressed. A detailed compilation of all relevant corrections and errors is given in Table I.

In this situation, with two detectors of very different statistical significance, we use the statistical average as the final neutrino asymmetry parameter result

$$B = 0.9802(50) = 0.9802(34)_{\text{stat}}(36)_{\text{syst}}. \qquad (6)$$

The experiment is limited by statistics and the uncertainty due to the displacement Δ between neutron beam and magnetic field. With two detectors of equal performance, both errors would be significantly smaller as the influence of Δ would cancel by calculating the arithmetic mean of B_1 and B_2.

The second case, electron and proton in opposite detectors, yields results with much larger uncertainties, 1.9% and 3.0% for detector 1 and 2, respectively, dominated by detector calibration. They statistically agree with (6).

Our result (6) has a precision similar to the most precise measurement so far [3] and agrees very well with all results published earlier. It is distinguished, however, as it features several times smaller corrections than competing experiments (0.5%; 1% if absolute numbers are considered cf. Table I). Our result is consistent with the standard model expectation, $B_{\text{SM}} = 0.9876(2)$, calculated with the current world average for λ from [11] and Eq. (2).

By including our result (6), the error of the world average for B reduces by 25%, yielding $\bar{B} = 0.9807(30)$. We apply this value to analyze a manifest LRS model with zero mixing ($\zeta = 0$), following the procedure described in [7] but with only the electron asymmetry parameter A from [11] as further input parameter; λ is a free parameter as it may be different from the SM value. We obtain a lower limit $m_{W_R} > 290.7 \text{ GeV}/c^2$ (90% C.L.). The rather small

improvement of this limit despite the reduced uncertainty of $\bar{B}$ originates from the shift of $\bar{B}$ to a lower value. Because of the controversial neutron lifetime (cf. [11]) we renounce a more elaborated analysis. However, with this controversy being settled, the improved neutrino asymmetry parameter together with other neutron decay data will permit the derivation of new limits on general LRS models and on scalar and tensor couplings.

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