Determination of the Weak Axial Vector Coupling $\lambda = g_A/g_V$ from a Measurement of the $\beta$-Asymmetry Parameter $A$ in Neutron Beta Decay

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We report on a new measurement of the neutron $\beta$-asymmetry parameter $A$ with the instrument PERKEO II. Main advancements are the high neutron polarization of $P = 99.7(1)\%$ from a novel arrangement of super mirror polarizers and reduced background from improvements in beam line and shielding. Leading corrections were thus reduced by a factor of 4, pushing them below the level of statistical error and resulting in a significant reduction of systematic uncertainty compared to our previous experiments. From the result $A_0 = -0.11996(58)$, we derive the ratio of the axial-vector to the vector coupling constant $\lambda = g_A/g_V = -1.2767(16)$.

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The Standard Model of weak $V-A$ interactions describes the $\beta^-$ decay of the free neutron $n \rightarrow p + e^- + \bar{\nu}_e$ implementing the following parameters: The vector coupling constant $g_V$ is defined by the product $G_F V_{ud}$ of the Fermi constant $G_F = g^2_{ew}/M_W^2$, where $g_{ew}$ is the electroweak coupling constant and $M_W$ is the $W$-boson mass, and the matrix element $V_{ud}$ of the quark mixing Cabbibo-Kobayashi-Maskawa (CKM) matrix. The axial current is renormalized by the strong interaction at low energy. $\lambda = g_A/g_V$ is defined as the ratio of the axial vector and vector coupling constants. $A$ is real, if the weak interaction is invariant under time reversal. Searches for time reversal violation can be found in [1, 2].

$\lambda$, $V_{ud}$, and neutron’s lifetime $\tau$ are interconnected by the following equation,

$$\tau^{-1} = C|V_{ud}|^2(1 + 3\lambda^2)f^R(1 + \Delta_R),$$  \hspace{1cm} (1)

where $C = G_F^2 m_e^2/(2\pi^2) = 1.1613 \times 10^{-4}s^{-1}$ in $h = c = 1$ units. $f^R$ is the phase space factor [3, 4] (including the model independent radiative correction) adjusted for the current value of the neutron-proton transition energy. $\Delta_R$ [5] is the model dependent radiative correction to the neutron decay rate. Thus $\lambda$ serves as input for a determination of either the CKM matrix-element $V_{ud}$ or the lifetime $\tau$. The Standard Model requests that the CKM matrix is unitary, a condition which is experimentally tested at the $10^{-4}$ level for the first row [6], and unitary tests are sensitive tools for searches for physics beyond the Standard Model. Previous determinations of $V_{ud}$ and $V_{us}$ raised questions about the unitarity of the CKM-matrix as discussed in [7–9]. Refs. [10–12] list several other motivations for a determination of $\lambda$ and searches for new symmetry concepts in neutron beta decay. In principle, the ratio $\lambda$ can be determined from QCD lattice gauge theory calculations, but the results of the best calculations vary by up to 30% [10]. The most precise experimental determination is from the $\beta$-asymmetry in neutron decay but previous experimental results are not consistent within their uncertainties [13].

In neutron decay, the probability that an electron is emitted with angle $\theta$ with respect to the neutron spin polarization $P = \langle \sigma_z \rangle$ is [14]

$$W(\theta) = 1 + \frac{v}{c}PA \cos(\theta),$$  \hspace{1cm} (2)

where $v$ is the electron velocity. $A$ is the parity violating $\beta$-asymmetry parameter which depends on $\lambda$. Accounting for order 1% corrections for weak magnetism $A_{\mu\mu}$, $g_V - g_A$ interference, and nucleon recoil, $A$ in Eq. (2) reads [3]

$$A = A_0(1 + A_{\mu\mu}(A_1W_0 + A_2W + A_3/W)), \hspace{1cm} (3)$$

with total electron energy $W = E_e/m_ec^2 + 1$ (endpoint $W_0$). The coefficients $A_{\mu\mu}$, $A_1$, $A_2$, $A_3$ are from [3] taking a different $\lambda$ convention into consideration. $A_0$ is a function of $\lambda$,

$$A_0 = -2\frac{\lambda(\lambda + 1)}{1 + 3\lambda^2}, \hspace{1cm} (4)$$

where we have assumed that $\lambda$ is real. In addition, a further small radiative correction [15] of order 0.1% must be applied.

In this letter, we present a new value for $\lambda$ derived from a measurement of the $\beta$-asymmetry $A$ with the instrument PERKEO II with strongly reduced systematic corrections and uncertainty. It was installed at the PF1B cold neutron beam position of the Institut Laue-Langevin (ILL) using a highly polarized cold neutron beam. Other correlation coefficients – the antineutrino-asymmetry parameter $B$ [16] and the proton-asymmetry parameter $C$ [17] – have been measured at this beam with the same instrument. Neutrons moderated by a cold source were guided via a neutron guide [18, 19] to the experiment and were then polarized using two super mirror
(SM) coated bender polarizers in crossed (X-SM) geometry [20]. An adiabatic fast passage (AFP) flipper allowed to invert the neutron spin direction. After a series of baffles for beam shaping, the transversally polarized neutron beam traversed the Perkeo II spectrometer and was absorbed in a beam dump. Two beam-line shutters, directly in front and behind the baffles, served to gain information on background [8, 21]. The main component of the Perkeo II spectrometer is a split-pair superconducting 1 T magnet providing \(2 \times 2\pi\) electron guidance from the full fiducial volume to either one of two plastic scintillator detectors with size 440 mm \(\times\) 160 mm (see the lower sketch in Fig. 1 of [22]). Details on the spectrometer and electron backscatter suppression can be found in [8, 21].

From the measured electron spectra \(N^i_e(E_e)\) and \(N^\uparrow_e(E_e)\) in the two detectors \((i = 1, 2)\) for neutron spin up and down, respectively, we define the experimental asymmetry as a function of electron kinetic energy \(E_e\) as

\[
A_{\text{exp},i}(E_e) = \frac{N^\uparrow_i(E_e) - N^\downarrow_i(E_e)}{N^\uparrow_i(E_e) + N^\downarrow_i(E_e)}. \tag{5}
\]

This experimental asymmetry is directly related to the asymmetry parameter \(A\), as follows from Eq. (2) and \(\langle \cos(\theta) \rangle = 1/2\):

\[
A_{\text{exp}}(E_e) = \frac{1}{2} AP f, \tag{6}
\]

with neutron polarization \(P\) and spin flip efficiency \(f\).

The main experimental errors of this measurement are due to statistics, detector response, neutron spin polarization, and background subtraction, see Tab. I. The four-fold intensity of the PF1B beam compared to the previous PF1 beam is used to enhance both statistics and systematics. The detected neutron decay rate within the fiducial volume was 375 s\(^{-1}\).

**Polarization:** The X-SM geometry efficiently suppresses garland reflections, resulting in a nearly wavelength- and angle-independent beam polarization. This dramatically reduces systematic uncertainties for determining the average beam polarization. Polarization measurements were performed employing time-of-flight behind a chopper to gain wavelength resolution. A second AFP flipper and two Schärpf polarizers [23, 24] in X-SM geometry as analyzers were used to measure the spin flip efficiency and for a rough determination of the beam polarization. Measurements in front and behind the Perkeo II spectrometer yielded consistent results. The absolute polarization was determined using a series of opaque \(^3\)He spin filter cells of different pressures and lengths, covering the wavelength range from 2 Å to 20 Å, see Fig. 1. Cells with both orientations of the \(^3\)He spin were used to increase sensitivity [25]. Wavelength averages were calculated taking into account the decay probability which is proportional to the measured capture spectrum. The spatial dependence was verified by measurements at five different positions across the neutron beam and found to be negligible. The resulting averages were \(P = 99.7(1)\%\) and \(f = 100.0(1)\%.\) Note that opaque \(^3\)He spin filters have an intrinsic accuracy of better than \(10^{-4}\) for polarization analysis [26].

![FIG. 1. Neutron polarization in the center of the Perkeo II beam. In order to cover the full spectrum with opaque \(^3\)He cells, 6 cells were used, with lengths of 25 cm or 10 cm and different pressures. In the legend, the effective pressures for a 10 cm cell are given. (Color online)](image1)

![FIG. 2. Difference of spectra in detector 1 for the second and the first beam line shutter closed, a measure for the background produced by the collimation system. The main part of the background is low energetic. In detector 2, the background looks similar.](image2)
tal background were used. This procedure reduces the data set to \(5.9 \times 10^7\) neutron decay events and increases the relative statistical error to \(3.8 \times 10^{-3}\) (compared to \(2.6 \times 10^{-3}\) in the preliminary analysis of [10, 27]). The trigger rate of \(500 \text{s}^{-1}\) comprises about \(120 \text{s}^{-1}\) from environmental background. The signal-to-background ratio in the fit region was better than \(8:1\).

Beam-related background is more difficult to address. In the PERKEO II spectrometer, the \(\beta\)-detectors are far off the beam at a transverse distance of \(960\,\text{mm}\). The beam line was optimized to place the last beam-defining baffle further away from the spectrometer than it was in our previous measurement [8]. The beam stop was positioned \(4\,\text{m}\) downstream of the decay volume. Baffles and beam stop were made from enriched \(^6\text{LiF}\) ceramics. The baffles’ lead supports shielded capture gammas (about \(10^{-4}\) per capture). Supports and beam line were protected against scattered neutrons by \(^6\text{LiF}\) rubber or boron glass. Halo baffles (not touching the beam) absorbed scattered neutrons close to the beam. Lead shielding was placed around the spectrometer to assure that gamma rays are scattered at least twice before they can reach a detector. In \(^6\text{LiF}\), about \(10^{-6}\) fast neutrons are produced per capture from \((t, n)\) reactions [28]. These neutrons were shielded by borated polyethylene (or, inside the beam stop vacuum, Plexiglas surrounded by borated glass) and secondary gammas by lead. The beam-related background was estimated from measurements with the two shutters using an extrapolation procedure described in [22] and confirmed by additional tests with external background sources. Compared to the previous measurement [8] of \(1/200\), it was reduced to \(1/1700\) of the electron rate in the fit region, which corresponds to \(0.11(2)\,\text{s}^{-1}\), see Fig. 2, resulting in a correction of \(1(1) \times 10^{-3}\). The assumed relative uncertainty of \(100\%\) is a very conservative estimate for this background extrapolation method.

**Detector response:** The plastic scintillators were read out by four photomultipliers per detector. Signals were integrated by charge-to-digital converters over a time interval that includes signals from backscattering. Trigger time differences between the detectors were registered to attribute the event in case of backscattering. The detector response function was determined and the detector stability was checked regularly using four mono-energetic conversion electron sources (\(^{109}\text{Cd}, ^{113}\text{Sn}, ^{207}\text{Bi}, \text{and } ^{137}\text{Cs}\)) on \(10\,\mu\text{g/cm}^2\) carbon backings, which were remotely inserted into the spectrometer. The branching ratios for K, L, M and N conversion electrons and the corresponding Auger electrons have been measured separately with silicon detectors [29] and were taken into account in the corresponding fit functions. Drift in the detector gain was smaller than \(1\%\) and corrected for. The detectors showed a small non-linearity at low energy. The largest systematic uncertainty is caused by the spatial non-uniformity of the detector response. Collected light output for electrons detected in the center of the scintillator was about \(5\%\) lower than for electrons detected at the ends. This spatial dependence was mapped using different calibration sources and was found to follow the expected cosh dependence. The detector gain, which has been used for the fit to the asymmetry parameter \(A\) of Eq. (6) and Fig. 4, was obtained by a fit to the spectrum \((N^+ - N^-)\), see Fig. 3, which is background free. A fit to \((N^+ + N^-)\) would yield a different gain resulting in a significant dependence of the asymmetry \(A\) on the lower limit of the fit region for detector 2.

**Backscattering:** By using the second detector as veto detector and carefully analyzing events with energies be-
the magnetic field, caused a difference of 1
placement between neutron beam and the maximum of
tector. This magnetic mirror effect, due to a small dis-
ing magnetic field, leading to detection in the wrong de-
calculated and is included in the fit function.

of the electron. The resulting correction can be reliably
by electron absorbing aluminum baffles. The absorption
depsends on the radius of gyration and thus on the energy of
the electron. The resulting correction can be reliably calculated and is included in the fit function.

**Edge effect:** The length of the decay volume is defined
by electron absorbing aluminum baffles. The absorption
depends on the radius of gyration and thus on the energy of
the electron. The resulting correction can be reliably calculated and is included in the fit function.

**Mirror effect:** Electrons can be reflected on an increas-
ing magnetic field, leading to detection in the wrong de-
tector. This magnetic mirror effect, due to a small dis-
placement between neutron beam and the maximum of
the magnetic field, caused a difference of 1.4% between
the asymmetries measured in the two detectors. Most of
this effect cancels by averaging the two detectors. The
remaining correction, due to the spacial extension of the
neutron beam, was calculated from the measured mag-
netic field geometry and neutron beam profile.

The experimental function $A_{\text{exp}}(E_{\text{n}})$ and a fit with a
single free parameter $\lambda$ are shown in Fig. 4 for both de-
tectors. The fit interval was chosen such as to minimize
effects due to non-linearity of the detector and unrec-
ognized background. From the experimental asymme-
tries we get $|A_0| = 0.11846(64)_{\text{stat}}$ for detector 1 and
$|A_0| = 0.12008(64)_{\text{stat}}$ for detector 2. All subsequent
corrections and uncertainties entering the final determi-
nation of $A_0$ are listed in Tab. I. After averaging and
orrecting for those small and mostly experimental sys-
tematic effects, we obtain

$$A_0 = -0.11996(45)_{\text{stat}}(37)_{\text{sys}} = -0.11996(58)$$

This value is consistent with our earlier result $[8]$ of $A_0 =
-0.1189(7)$. The combined results of the new and our
previous $[8, 21]$ experiments are

$$A_0 = -0.11951(50)$$

In the average Eq. (8) we have accounted for correla-
tions of systematic errors in the experiments. Conserva-
tively, errors concerning detector calibration and unifor-
mity, background determination, edge effect and the ra-
diative correction were considered correlated on the level
of the smallest error of all three experiments.

Other experiments $[31–33]$ gave significantly lower val-
ues for $|\lambda|$. However, in all these experiments large cor-
rections had to be applied for neutron polarization, mag-
netic mirror effects, solid angle, or background, which
were in the 15% to 30% range. In our present experi-
ment, all individual corrections are below $3 \times 10^{-3}$ and
the sum of their absolute values is below 1%. We there-
fore use only the value given in Eq. (8) for further dis-
cussion. The determination of $\lambda = -1.27590^{+0.00449}_{-0.00445}$
by the UCNA collaboration $[34]$ is in agreement with this
result, albeit with a larger error.

Assuming the $V–A$ structure of the Standard Model,
neutron lifetime can be determined using the $\mathcal{F}l$ value
from nuclear beta decay

$$\tau_n = \frac{2}{\ln 2} \frac{\mathcal{F}l}{f_R (1 + 3 \lambda^2)}.$$  

where the phase space factor $f_R = 1.71385(34)$ $[4]$ in-
cludes radiative corrections. We use our result Eq. (8)
and $\mathcal{F}l = 3071.81(83)$ $[6]$ to derive the neutron lifetime

$$\tau_n = 879.4(1.6) \text{s}.$$  

This result is in agreement with and nearly as precise
as the current world average $\tau_n = 881.9(1.3) \text{s}$ $[12]$ that
includes a scale factor of 2.5.

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