PRECISION MEASUREMENTS IN NEUTRON DECAY

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We present new precision measurements of angular correlation coefficients in polarized neutron decay. We have obtained values for the electron asymmetry coefficient A, the neutrino asymmetry coefficient B, and for the proton asymmetry coefficient C. In combination with other results, the new measurements are used to derive limits on “Physics beyond the Standard Model”.

1 Introduction

Free neutrons decay with a mean lifetime τ_n of about 15 minutes in electron, proton, and electron anti-neutrino: $n \to e^- \; p \; \overline{\nu}_e$. The maximal kinetic energy of the electron is $E_{\rm max}(e) =$ 782 keV. For the proton, $E_{\rm max}(p) = 780$ eV is three orders of magnitude smaller. Neutron decay – involving all particles of the first generation – constitutes an ideally suited laboratory to do particle physics at very low energies as it provides important information on the structure of the weak interaction an the underlying symmetries. It is a quite simple system where theoretical corrections are small and no nuclear structure effects have to be considered.

Our observables are angular correlations between neutron spin and the momentum of the three decay products. The decay probability dω of polarized neutrons can be expressed in terms of two of these “asymmetries”, the electron asymmetry A and the neutrino asymmetry B [1]:

$$\mathrm{d}\omega \propto |V_{ud}|^2 \left(1 + a \, \frac{p_e p_\nu}{E E_\nu} + \langle s_n \rangle \left[A \, \frac{p_e}{E} + B \, \frac{p_\nu}{E_\nu} \right] \right) . \tag{1}$$

E, E_ν, p_e, and p_ν are energy and momentum of electron and neutrino respectively, $\langle s_n \rangle$ denotes the neutron spin, and $|V_{ud}|$ is the first entry of the quark mixing matrix. a is the correlation between electron and neutrino momentum. The proton asymmetry C does not enter this expression, but it is kinematically coupled to A and B via [2] $C = x_C(A + B)$, where $x_C = 0.27484$ is a kinematical factor. In the standard $V - A$ formulation of weak interactions, all correlations are functions of one single parameter $\lambda = g_A/g_V$, the ratio of axial-vector and vector coupling constant (assuming λ to be real and neglecting weak magnetism and other recoil effects):

$$a = \frac{1-\lambda^2}{1+3\lambda^2}, \quad A = -2\,\frac{\lambda^2+\lambda}{1+3\lambda^2}, \quad B = 2\,\frac{\lambda^2-\lambda}{1+3\lambda^2}, \quad C = x_C\,\frac{4\,\lambda}{1+3\lambda^2}. \tag{2}$$

The precise determination of λ is important as the calculation of many processes in cosmology (e.g. primordial element formation), astronomy (e.g. solar cycle, neutron star formation), and particle physics (e.g. neutrino detectors, neutrino scattering) depends on this parameter. The observable most sensitive to λ is the electron asymmetry A, however, it can be also extracted from measurements of a and C.

Within the Standard Model, neutron decay can be described with the two parameters λ and V_{ud} only. But since much more observables are accessible (various correlation coefficients and the lifetime τ_n) the problem is overdetermined, and neutron decay can be used to test the Standard Model and to search for new physics. In section 3, we will present neutron limits for additional right-handed $(V + A)$ currents and anomalous couplings (scalar and tensor) in the interaction.

2 Experiment and Results

The measurements were performed using the electron spectrometer PERKEO II. It features a pair of superconducting coils in a split pair configuration that generate a slightly decreasing magnetic field ($B_{\max} \approx 1$ T) perpendicular to the spin polarized neutron beam crossing the spectrometer (cf. fig. 1). The instrument was installed at the cold neutron beam position PF1B at the Institut Laue-Langevin (ILL), Grenoble.

The magnetic field fulfills several functions: It separates the full solid angle into two hemispheres since the spins align with the field lines: The momentum projection of the decay particle onto the neutron spin determines whether the particle is emitted in neutron spin direction or against it. The field guides the charged decay products onto the two detectors, installed at both sides next to the beam, providing full $2 \times 2\,\pi$ detection. The detectors consist of plastic scintillators with photomultiplier readout. In order to measure the very low energetic protons with the same detector (necessary for neutrino and proton asymmetry), we developed a special

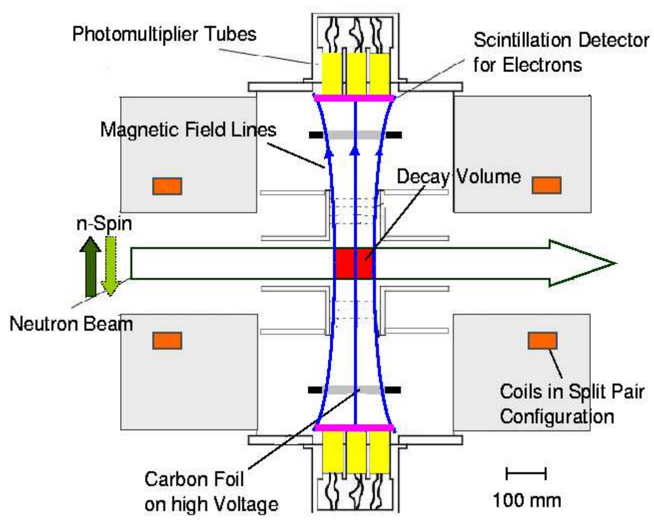

Figure 1: Electron spectrometer PERKEO II: Transversally polarized neutrons transit the instrument, their spins are aligned with the magnetic field, which separates the full solid angle into two hemispheres covered by a detector each.

setup to convert protons into electrons [3,4]: Protons were accelerated onto a very thin carbon foil on negative high voltage where they had enough ionization power to generate one or more secondary electrons. These could be detected by the scintillators.

2.1 Electron Asymmetry A and λ

The experimental signature of the electron asymmetry is

$$A_{\text{exp}}(E) = \frac{N^+(E) - N^-(E)}{N^+(E) + N^-(E)} = \frac{1}{2}\frac{v}{c} A\ P\ F, \tag{3}$$

where $N(E)$ is the number of electrons with energy E and the sign denotes whether the electron was emitted in (+) or against (−) neutron spin direction. This expression holds for both detectors separately since a spinflipper was used to periodically turn the neutron spin by 180°. It is related to the angular correlation coefficient A via the second equation in (3). v/c is the electron velocity in terms of the speed of light, P the neutron polarization, and F the spinflipper efficiency. With new methods to polarize the beam and to analyze the beam polarization [5] we managed to achieve a much improved beam polarization compared to former measurements.

Background generated in the neutron collimation system and at the beamstop at the end of the installation was heavily suppressed. The remaining background leads to a small uncertainty of 0.1 %. For future measurements, the spectrometer PERKEO III [6] has been developed: It can be operated with a chopped neutron beam allowing to acquire data only when no background is generated.

About 160 million events were recorded and the measurement is still limited by statistics. Details on the experiment can be found in [7]. For the following analysis, we will use the value $A_{\text{PII}} = -0.1193(4)$ – corresponding to $\lambda_{\text{PII}} = -1.2749(11)$, the average of the new preliminary result and former PERKEO II measurements [8].

2.2 Neutrino Asymmetry B

In our setup, the neutrino could not be detected directly, thus it had to be reconstructed from a coincident measurement of electron and proton. The case where both are emitted into the same hemisphere is most sensitive to the neutrino asymmetry B [9]. Here, the experimental asymmetry is defined using the electron spectra Q^{ij}

$$B_{\text{exp}}(E) = \frac{Q^{--}(E) - Q^{++}(E)}{Q^{--}(E) + Q^{++}(E)}, \tag{4}$$

where the first sign indicates the emission direction of the electron, the second denotes the proton.

A fit to the combined data is shown in figure 2. The result (for details cf. [4])

$$B_{\text{PII}} = 0.9802(50) \tag{5}$$

is almost independent from detector calibation due to the flat characteristics of the spectrum. It has an uncertainty that is comparable to the most precise measurement so far [10] but has significantly lower corrections. The result is limited by statistics and the error in the relative position between the magnetic field of the spectrometer and the neutron beam maximum. A misalignment would cause some charged particles to be reflected at the increasing magnetic field ("magnetic mirror") leading to signals in the wrong detector.

The new result agrees with the Standard Model expectation (calculated with eq. (2) and the current PDG value for λ) and previous measurements [10,11]. Averaging all yields the new world mean value with an uncertainty lowered by 25 %:

$$B_{\text{mean}} = 0.9807(30). \tag{6}$$

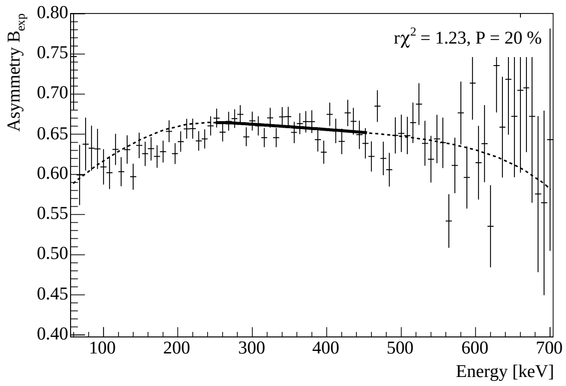

Figure 2: Experimental neutrino asymmetry B_{exp}. The solid line indicates the fit region, the dashed line the fit extension. The result does not depend on the fit region. Increasing the region to higher energies would increase the systematic error due to the magnetic mirror effect.

2.3 Proton Asymmetry C

The combined electron-proton detector only allows to measure the emission direction of the proton, a determination of its energy is impossible since it is much smaller than the electron energy. Therefore we have to obtain the proton asymmetry C from the coincident measurement in an integral way. For both detectors, altogether four electron energy spectra generated with certain conditions on the emission direction of electrons (first) and protons (second sign) are available:

$$Q^{++}(E), \quad Q^{-+}(E), \quad Q^{--}(E), \quad Q^{+-}(E). \tag{7}$$

Now, the proton asymmetry is defined using the integrals of these spectra

$$C = \frac{\int (Q^{++}(E) + Q^{-+}(E))\mathrm{d}E - \int (Q^{--}(E) + Q^{+-}(E))\ \mathrm{d}E}{\int (Q^{++}(E) + Q^{-+}(E))\mathrm{d}E + \int (Q^{--}(E) + Q^{+-}(E))\mathrm{d}E}. \tag{8}$$

The integrals were obtained from one-parameter fits to the Q^{ij} spectra in a fit region that was well above the detection threshold and remaining background contributions. After extrapolation to the whole energy range, the functions were integrated. This yields the result [12]

$$C_{\text{PII}} = -0.2377(36). \tag{9}$$

With an uncertainty of 1.5 %, this constitutes the first precision measurement of this observable. The error is dominated by energy calibration and extrapolation, however, at the moment the proton asymmetry is known more precisely than the electron-neutrino correlation a.

3 Neutron Decay Limits on New Physics

We use the new results in combination with other measurements to set limits on possible contributions of new physics to neutron decay. Another important input parameter is the neutron lifetime τ_n. At the moment, however, the experimental situation concerning τ_n is quite unclear, since there is one new measurement [13] deviating by 6.5 σ from the average of previous results. In order to account for this discrepancy we enlarge all quoted errors with a scaling factor 2.5 to obtain statistical agreement ($\chi^2/\text{NDF} = 1$) and get the average $\tau_{\text{mean}} = 882.0(14)$ s.

3.1 Right-Handed Currents

Parity is maximally violated in the Standard Model, i.e. the weak interaction couples only to left-handed particles. However, the model only describes but gives no intrinsic motivation for parity violation. According to simple extensions of the Standard Model, the *Left-Right Symmetric Models*[14,15], parity violation stems from a spontaneous symmetry breaking at mass scale m_2. Below this energy, the interaction is mediated by the usual W_L-bosons, however, there should be additional heavy bosons W_R, remnants of a right-handed $SU(2)_R$ group. The *Manifest Left-Right Symmetric Model*[16] assumes that left- and right-handed quark mixing matrices are equal. Here, the weak eigenstates $W_{L,R}$ are linear combinations of the mass eigenstates $W_{1,2}$,

$$W_L = \cos\zeta \; W_1 - \sin\zeta \; W_2 \qquad \text{and} \qquad W_R = e^{i\phi}\sin\zeta \; W_1 + e^{i\phi}\cos\zeta \; W_2, \tag{10}$$

with mixing angle ζ and a CP violating phase ϕ (we will neglect ϕ in the following since it has no observable effect). Additional parameters of the theory are the mass ratio $\delta = m_1^2/m_2^2$ and the coupling constant ratio $\lambda' = g'_A/g'_V$.

If one extends equations (2) and the expression for the lifetime τ_n to account for possible right-handed admixtures, one can generate exclusion plots and derive limits. The neutron decay result for the input parameters A_{PII}, B_{mean}, and τ_{mean} is given in figure 3 showing a projection along the λ' axis onto the $\zeta - \delta$ plane. The 90 % confidence level (CL) limits are $-0.1968 < \zeta < 0.0040$ and $\delta < 0.0885$ which yields $m_2 > 270$ GeV.

There are tighter limits on the mass m_2 from direct W' searches at Tevatron[17], and better constraints on ζ from muon decay tests[18], however, in the mass range not excluded by the collider results the neutron limits for the mixing angle ζ are more stringent. And when one considers more general left-right symmetric models, results from β-decay, muon decay, and direct searches are complementary[19].

3.2 Scalar and Tensor Couplings

In the framework of the Standard Model, the weak interaction includes only vector (V) and axial-vector (A) couplings. However, the most general Lorentz invariant Lagrangian[20]

$$\mathcal{L} = \sum_k \; (\overline{p}\Omega_k n) \; (\overline{e}\Omega_k(g_k + g'_k\gamma^5)\nu_e) + \text{h.c.} \tag{11}$$

allows also scalar (S) and tensor (T) contributions, where the operator Ω_k ($k = V, A, S, T$) describes the kind of interaction. Again, equations (2) were extended to account for additional

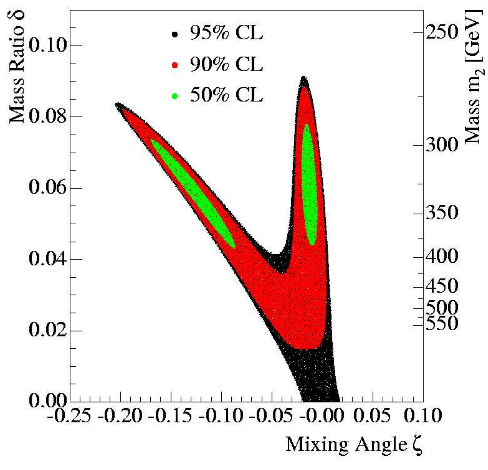

Figure 3: Exclusion plot on possible admixtures of right-handed ($V+A$) couplings in the weak interaction derived from neutron decay observables. The Standard Model, $\zeta = \delta = 0$, is included with 95 % CL.

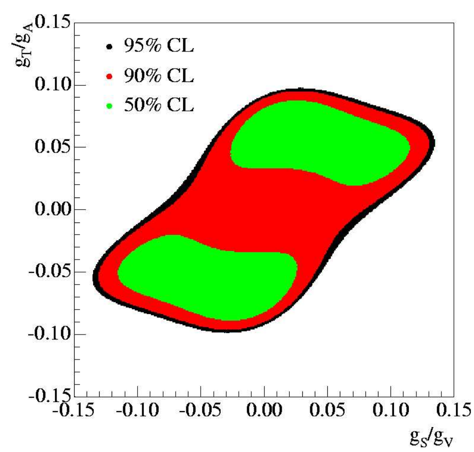

Figure 4: Neutron decay limits on anomalous (scalar g_S and tensor g_T) couplings in the weak Lagrangian. The Standard Model $g_S = g_T = 0$ is included in the 90 % CL contour.

couplings g_S, g_T in the simple *Right-Handed Scalar and Tensor Model*[19]. It assumes $g'_V/g_V = 1$, $g'_A/g_A = 1$, $g'_S/g_V = -g_S/g_V$, and $g'_T/g_A = -g_T/g_A$ leading to left-handed V, A and right-handed S, T couplings. The result of a χ^2-scan based on the input parameters A_{PII}, B_{mean}, C_{PII}, $a = -0.103(4)$ [21], and τ_{mean} is shown in fig. 4. The 90 % CL limits, $|g_S/g_V| < 0.130$ and $|g_T/g_A| < 0.0948$, agree with the Standard Model case $g_S = g_T = 0$.

Scalar contributions seem to be almost excluded by an analysis of superallowed β-decays giving the constraint $|g_S/g_V| < 0.0013$ when the conserved vector current hypothesis (CVC) is assumed [22]. For tensor contributions, however, neutron decay provides excellent limits.

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