Is the Unitarity of the Quark-Mixing CKM Matrix Violated in Neutron β-Decay?

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We report on a new measurement of neutron β-decay asymmetry. From the result $A_0 = -0.1189(7)$, we derive the ratio of the axial vector to the vector coupling constant $\lambda = g_A/g_V = -1.2739(19)$. When included in the world average for the neutron lifetime $\tau = 885.7(7)$ s, this gives the first element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix V_{ud}. With this value and the Particle Data Group values for V_{us} and V_{ub}, we find a deviation from the unitarity condition for the first row of the CKM matrix of $\Delta = 0.0083(28)$, which is 3.0 times the stated error.

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As is well known, the quark eigenstates of the weak interaction do not correspond to the quark mass eigenstates. The weak eigenstates are related to the mass eigenstates in terms of a 3×3 unitary matrix V, the so called Cabibbo-Kobayashi-Maskawa (CKM) matrix. By convention, the u, c, and t quarks are unmixed and all mixing is expressed via the CKM matrix V operating on d, s, and b quarks. The values of individual matrix elements are determined from weak decays of the relevant quarks. Unitarity requires that the sum of the squares of the matrix elements for each row and column be unity. So far precision tests of unitarity have only been possible for the first row of V, namely

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta . \qquad (1)$$

In the standard model, the CKM matrix is unitary with $\Delta = 0$. Usually, $|V_{ud}|$ is derived from superallowed nuclear β-decay experiments to $|V_{ud}| = 0.9740(5)$. This value includes nuclear structure effect corrections. Combined with kaon-, hyperon- and B decays, this leads to $\Delta = 0.0032(14)$, signaling a deviation from the unitarity condition by 2.3σ standard deviation [1]. However, some of the nuclear corrections are difficult to calculate, and therefore the Particle Data Group [2] doubles the error in $|V_{ud}|$.

A violation of unitarity in the first row of the CKM matrix is a challenge to the three generation standard model. The data available so far do not preclude there being more than three generations; CKM matrix entries deduced from unitarity might be altered when the CKM matrix is expanded to accommodate more generations [2,3]. A deviation Δ has been related to concepts beyond the standard model, such as couplings to exotic fermions [4,5], to the existence of an additional Z boson [6,7], or to the existence of right-handed currents in the weak interaction [8]. Nonunitarity of the CKM matrix in models with an extended quark sector give rise to an induced neutron electric dipol moment that can be within reach of the next generation of experiments [9].

In this article, we derive $|V_{ud}|$, not from nuclear β decay, but from neutron decay data. In this way, the unitarity check of (1) is based solely on particle data, i.e., neutron β decay, K decays, and B decays, where theoretical uncertainties are significantly smaller. So much progress has been made using highly polarized cold neutron beams with an improved detector setup that we are now capable of competing with nuclear β decays in extracting a value for V_{ud}, while avoiding the problems linked to nuclear structure.

In the standard model, the Lagrangian of neutron decay is restricted to

$$\mathcal{L}_{\text{int}} = \frac{G_F}{\sqrt{2}} V_{ud} \cdot \{\bar{p}[\gamma^\mu(1 + \lambda\gamma_5) + \frac{\mu_p - \mu_n}{2m_p}\sigma_{\mu\nu}q^\nu]n \cdot \bar{e}\gamma^\mu(1 - \gamma_5)\nu\}. \qquad (2)$$

G_F is the Fermi decay constant; n, p, e, and ν are spinors describing neutron, proton, electron, and neutrino; λ is the ratio of the axial vector to the vector coupling constant g_A/g_V; and q is the momentum transfer between hadrons and leptons. The term $(\mu_p - \mu_n)/2m_p$ is the weak magnetism contribution, which is linked to μ_p and μ_n, the anomalous magnetic moments of proton and neutron. m_p is the nucleon mass. In Eq. (2), we omitted the second-class induced scalar form factor f_3 and the induced pseudotensor form factor g_2, because second class currents are excluded in the standard model. The first-class induced pseudoscalar form factor g_3 is negligible in neutron decay and constrained by the Goldberger-Treiman relation.

Since G_F is known from muon decay, in the standard model only two additional parameters are needed to describe free neutron decay, namely λ and V_{ud}. In principle, the ratio λ can be determined from QCD lattice gauge theory calculations, but the results of the best calculations vary by up to 30%. Today therefore all weak semileptonic particle cross sections used in cosmology, astrophysics, and particle physics have to be calculated from neutron decay data.

A neutron decays into a proton, an electron, and an electron antineutrino. Observables are the neutron lifetime τ and spins $\sigma_e, \sigma_\nu, \sigma_p$, and momenta p_e, p_ν, p_p of the electron, antineutrino, and proton, respectively. The electron spin, the proton spin, and the antineutrino are not usually observed. The lifetime is given by

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

where $C = G_F^2 m_e^5/(2\pi^3) = 1.1613 \cdot 10^{-4}\ \mathrm{s}^{-1}$ in $\hbar = c = 1$ units, $f^R = 1.714\,82(15)$ is the phase space factor [10] (including the model independent radiative correction) adjusted for the current value of the neutron-proton transition energy. $\Delta_R = 0.0240(8)$ [1,11] is the model dependent radiative correction to the neutron decay rate, of which 0.0212 is straightforward electroweak-asymptotic QCD contribution, whereas the remaining 0.0028 depends on the strong interaction models. The neutron β-decay rate and its relevant uncertainties at the 10^{-4} level were reviewed recently [12,13].

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

$$W(\vartheta) = 1 + \frac{v}{c} PA\cos(\vartheta), \qquad (4)$$

where v/c is the electron velocity expressed in fractions of the speed of light. A is the β-asymmetry coefficient which depends on λ. On account of order 1% corrections for weak magnetism, $g_V - g_A$ interference, and nucleon recoil, A has the form $A = A_0[1 + A_{\mu\mathrm{m}}(A_1 W_0 + A_2 W + A_3/W)]$ with electron total energy $W = E_e/m_e c^2 + 1$ (end point W_0). A_0 is a function of λ

$$A_0 = -2\frac{\lambda(\lambda + 1)}{1 + 3\lambda^2}, \qquad (5)$$

where we have assumed that λ is real. The coefficients $A_{\mu\mathrm{m}}, A_1, A_2, A_3$ are from [10] taking a different λ convention into consideration. In addition, a further small radiative correction [15] of order 0.1% must be applied. Other correlation coefficients (not measured in our experiment) are the antineutrino-electron correlation a, the antineutrino-asymmetry correlation B, and the time-reversal-violating triple correlation coefficient D. They also depend on λ. Hence, various observables are accessible to experiment, so that the problem in extracting λ and $|V_{ud}|$ is overdetermined and, together with other data from particle and nuclear physics, many tests of the standard model become possible. Of course, a pertinent determination of the radiative corrections of Eq. (3) remains an important task.

In the following section we report on our new measurement of the neutron β-asymmetry coefficient A with the instrument PERKEO II, and on the consequences for $|V_{ud}|$. Our first measurement [16] with this new spectrometer gave a value for A_0 which differed significantly from the combined previous data. In light of this we decided to remeasure coefficient A_0 with an improved setup. The new result confirms our earlier finding, with a reduced error but same result. PERKEO II was installed at the PF1 cold neutron beam position at the High Flux Reactor at the Institut Laue-Langevin, Grenoble. Cold neutrons are obtained from a 25 K deuterium cold moderator near the core of the 57 MW uranium reactor. The neutrons are guided via a 60 m long neutron guide of cross section $60 \times 120\ \mathrm{mm}^2$ to the experiment and are polarized by a supermirror polarizer of $30 \times 45\ \mathrm{mm}^2$ cross section. The de Broglie wavelength spectrum of the cold neutron beam ranges from about 0.2 to 1.3 nm. Above a wavelength of $\lambda > 1.3$ nm, a very high degree of polarization is difficult to achieve. A long wavelength cutoff filter just in front of the supermirror polarizer removes these undesired neutrons from the beam [17]. The degree of neutron polarization was measured to be $P = 98.9(3)\%$ over the full cross section of the beam. The polarization efficiency was monitored and it remained constant during the whole experiment. The neutron polarization is reversed periodically with a current sheet spin flipper, with measured spin flip efficiency of $f = 99.7(1)\%$.

The main component of the PERKEO II spectrometer is a superconducting 1 T magnet in a split pair configuration, with a coil diameter of about 1 m. Neutrons pass through the spectrometer, whereas decay electrons are guided by the magnetic field to either one of two scintillation detectors with photomultiplier readout. The detector's solid angle of acceptance is truly $2 \times 2\pi$ above a threshold of 60 keV. Electron backscattering effects, serious sources of systematic error in β spectroscopy, are effectively suppressed. Technical details about the instrument can be found in [18].

The measured electron spectra $N_i^\uparrow(E_e)$ and $N_i^\downarrow(E_e)$ in the two detectors ($i = 1, 2$) for neutron spin up and down, respectively, define the experimental asymmetry as a function of electron kinetic energy E_e

$$A_{i_{\mathrm{exp}}}(E_e) = \frac{N_i^\uparrow(E_e) - N_i^\downarrow(E_e)}{N_i^\uparrow(E_e) + N_i^\downarrow(E_e)}. \qquad (6)$$

By using (4) and with $\langle\cos(\vartheta)\rangle = 1/2$, $A_{i_{\mathrm{exp}}}(E)$ is directly related to the asymmetry parameter

$$A_{\mathrm{exp}}(E_e) = A_{1_{\mathrm{exp}}}(E_e) - A_{2_{\mathrm{exp}}}(E_e) = \frac{v}{c} APf. \qquad (7)$$

The main experimental errors are due to *neutron spin polarization, background subtraction, and detector response.* To analyze the *neutron spin polarization,* a special setup of three additional spin flippers and two supermirror polarizers was used [19]. This gave an uncertainty of 0.3% in the measured beam polarization. As a very precise cross check, in a separate setup, neutron polarization was measured again with three completely different methods: first, with our supermirror setup, second, with a new method using an almost opaque ^{3}He spin filter [20,21], and third, with a polarized proton filter [22]. The results of all three measurements agree to within 0.15%.

A correction of 0.5% on A is due to *background subtraction.* One main feature of the PERKEO II spectrometer is its high β-decay count rate of about 270 s^{-1} due to a large decay volume ($80 \times 80 \times 270$ mm^3) and a 4π detector. As a consequence, the signal-to-background rate in the range of interest (Fig. 1) was 7:1. Most of the background is environmental and was measured separately and subtracted from the data. Extreme care is required to suppress any beam-related background, as discussed in [16]. The beam divergence was limited to 12 mrad by appropriate neutron baffles upstream, made from enriched ^{6}LiF plates. The beamstop was positioned 6 m downstream of the decay volume. The β detectors were installed far off the beam at a transverse distance of 960 mm, and had no direct view to the polarizer, the baffles, or the beam stop. Any beam-related gamma quantum had to undergo multiple directional changes before reaching the detector. Compared with our previous measurement with the same apparatus [16], this beam-related background was reduced by a factor of 3 to 0.3 s^{-1} or to 1:200 of the signal rate. Thus, in the fit interval the size of the background correction is 0.5%. This beam-related background was determined using an extrapolation procedure described in [16] and [18]. The relative uncertainty of 50% is a conservative estimate of this background extrapolation method (see Table I).

The *detector response function* was determined with six conversion line sources on 10 $\mu g/cm^2$ carbon backings, which were remotely inserted into the spectrometer. The K, L, M, and N conversion electrons and the corresponding Auger electrons are taken into account. Detector response is linear in energy within 1% leading to an uncertainty of 0.2% in A [18].

The experimental function $A_{i_{\rm exp}}(E_e)$ and a fit with one free parameter $A_{i_{exp}}$ (the absolute scale of A_0) is shown in Fig. 1. The χ^2 is 142.5 for detector one and χ^2 is 129 for detector two for 150 degree of freedom. The fit interval was chosen such that the signal-to-background ratio was at maximum. The parameter $A_{i_{\rm exp}}$ is directly related to the asymmetry parameter via $A_{i_{\rm exp}} = A_0 \cdot P \cdot f$. From the experimental asymmetries we get $A_{1_{\rm exp}} = -0.1174(7)$ and $A_{2_{\rm exp}} = -0.1163(7)$ for detector 1 and detector 2, respectively. All corrections and uncertainties entering the determination of A are listed in Table I. The corrections marked with an "a" are already included in the fit. After correcting for the other small experimental systematic effects listed in Table I, we obtain $A_0 = -0.1189(8)$. This value is identical to our earlier result [16] of $A_0 = -0.1189(12)$, but with a smaller error. The combined result is

$$A_0 = -0.1189(7) \quad \text{and} \quad \lambda = -1.2739(19). \tag{8}$$

With this value, and the world average value for $\tau = 885.7(7)$ s from [2], we find from (3) that

$$|V_{ud}| = 0.9713(13). \tag{9}$$

TABLE I. Experimental corrections and uncertainties entering the determination of A.

Effect	Correction	Error
Polarization analysis		
Polarization efficiency	1.1%	0.3%
Spinflip efficiency	0.3%	0.1%
Data set		
Statistics		0.45%
Background	0.5%[a]	0.25%
Detector response		
Linearity		0.2%
Width and pedestal		0.1%
Drifts		0.06%
Edge effect	−0.24%[a]	0.1%
Hemisphere integration		
Mirror effect	0.09%	0.02%
Backscattering	0.2%	0.17%
Radiation corrections	0.09%	0.05%
Sum	2.04%	0.68%

[a]Already included in the fit function of Fig. 1.

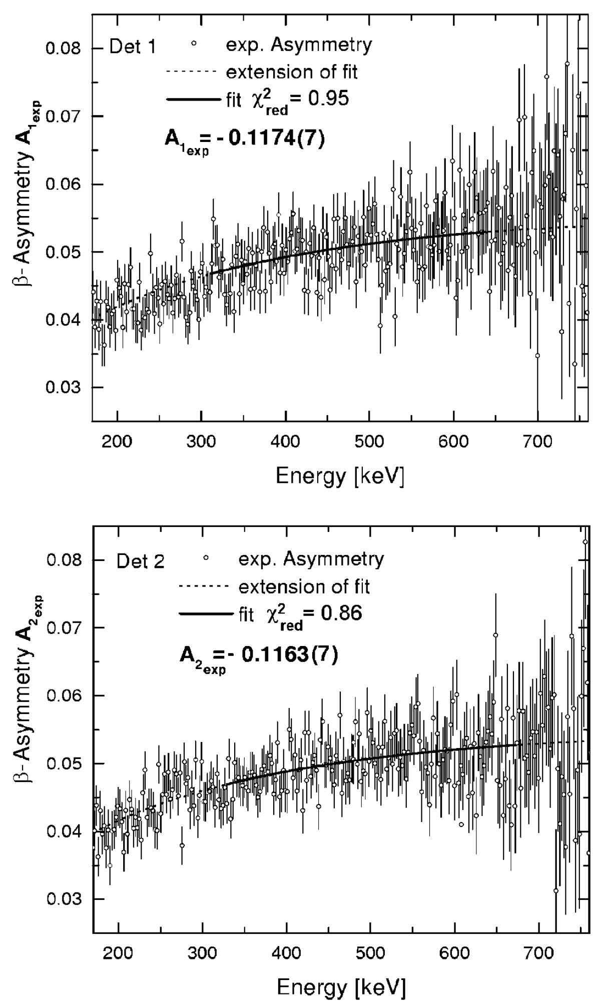

FIG. 1. Fit to the experimental asymmetry $A_{\rm exp}$ for detector 1 and detector 2. The solid line shows the fit interval, whereas the dotted line shows an extrapolation to higher and lower energies.

With [2] $|V_{us}| = 0.2196(23)$ and the negligibly small $|V_{ub}| = 0.0036(9)$, we obtain

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta = 0.9917(28). \quad (10)$$

This value differs from the standard model prediction by deviation $\Delta = 0.0083(28)$, or 3.0 times the stated error.

Earlier experiments [23–25] gave significantly lower values for $|\lambda|$. However, in all these earlier experiments large corrections had to be made for neutron polarization, electron-magnetic mirror effects, or background, which were all in the 15% to 30% range. In our experiment, on the other hand, the total correction to the raw data is 2.0%, i.e., 10 times less than in earlier experiments. We therefore believe that our new experiment is more reliable than previous experiments.

Averaging over our new result and previous neutron β-decay results the Particle Data Group [26] arrives at a new world average for $|V_{ud}|$ from neutron β decay which leads to only a 2.2σ deviation from unitarity.

The Particle Data Group obtains from superallowed $0^+ \rightarrow 0^+$ transitions a value $|V_{ud}| = 0.9740(10)$. This value is compatible with our value (9) at the 90% C.L.

An independent test of CKM unitarity comes from W physics at LEP [27] where W decay hadronic branching ratios can be used. Since decay into the top quark channel is forbidden by energy conservation one would expect $\sum |V_{ij}|^2$ to be 2 with a three generation unitary CKM matrix. The experimental result is 2.032(32), consistent with (10) but with considerably lower accuracy.

In the frame of the present article we do not want to speculate on the origin of the deviation Δ. Nevertheless, we want to point out that it is unlikely that this deviation is due to induced form factors (as discussed above) or erroneous radiative corrections or to the other CKM elements V_{us} and V_{ub}. A nonzero second-class term g_2 (in contradiction to the standard model) is unlikely because the present experimental limit on $g_2 < 0.2$ [28] would lead to a change in the neutron decay-asymmetry A_0 by less than 0.15%. If the deviation Δ was due to the radiative correction Δ_R, then the error on Δ_R must be more than 9 times larger than the quoted error. Also it is unlikely that a nonzero Δ is due to an error in the determination of the high energy results on V_{us} because the error in V_{us} must be enlarged by factors of 8 to explain our value of Δ (the value of V_{ub} is completely negligible in this context).

In summary, $|V_{ud}|$, the first element of the CKM matrix, has been derived from neutron decay experiments in such a way that a unitarity test of the CKM matrix can be performed based solely on particle physics data. With this value, we find a 3σ standard deviation from unitarity, which conflicts the prediction of the standard model of particle physics.

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