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Determination of $|V_{ud}|$ – Overview

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The present status and the future direction of the experimental $|V_{ud}|$ determination are reviewed with an emphasis on the ongoing and future neutron experiments.

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1. Introduction

High precision electroweak measurements provide stringent tests of the standard model (SM) and search for what may lie beyond it. A deviation from expectations based on our knowledge of the SM would be indirect evidence for new physics. These high precision tests complement direct searches for new physics using high energy colliders.

Unitarity of the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix) requires that the first row satisfy

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1. \tag{1.1}$$

A deviation from unity could arise from additional heavy quark mixing. Also, because the extraction of these CKM matrix elements involves comparison between muon decay and semileptonic decay of hadrons, any new physics that causes a violation of quark-lepton universality would cause a deviation from unity.

The value of $|V_{ud}|$ is determined by comparing the vector coupling constant of β decay, G_V, to the Fermi coupling constant, G_F, determined from muon decay. The value of G_V can be determined from superallowed nuclear β decays, neutron β decay, and pion β decay.

In all three cases, a small radiative correction needs to be applied in extracting the value of $|V_{ud}|$ in order to account for quantum loop effects [1, 2].

In addition, for nuclear β decay, additional corrections are necessary to account for the fact that the β decay of the nucleon occurs inside a nucleus. Despite larger corrections, currently the determination of $|V_{ud}|$ from supperallowed nuclear β decays, based on measurements of the strength of a dozen or so different transitions, provides the most precise value [3, 4]. The experimental uncertainties have become so well controlled that theoretical uncertainties associated with these corrections dominate the uncertainty quoted on the value of $|V_{ud}|$. The current experimental program on superallowed β decays is aimed at reducing the nuclear structure dependent theoretical uncertainties by systematically measuring the transition strength of wider varieties of nuclear species.

Because neutron β decay is a mixed transition, determination of $|V_{ud}|$ from neutron β decay requires knowledge of the neutron lifetime τ_n and the ratio of the axial to vector coupling constants $\lambda = G_A/G_V$. Despite the smaller corrections, and therefore the potential for a more precise determination of $|V_{ud}|$, because of experimental difficulties, the value of $|V_{ud}|$ from neutron β decay is not competitive yet. However, with more intense sources of cold and ultracold neutrons becoming available and with improved experimental techniques being developed, determination of $|V_{ud}|$ from neutron β decay with a similar precision to that from nuclear β decay is within reach. This will provide a useful cross check of the current determination of $|V_{ud}|$ from nuclear β decays, in particular of the nuclear dependent corrections. Furthermore, precision measurements of neutron decay parameters hold the most promise for a further improvement of the determination of $|V_{ud}|$.

Pion β decay is even more challenging experimentally because the branching ratio for this β decay is only 10^{-8}. Even though the experimental uncertainty has been significantly reduced by the recent PIBETA experiment [5], the uncertainties for $|V_{ud}|$ from pion β decay is much larger than either of the other two approaches.

In the following, after a brief review of the status and the future direction of the $|V_{ud}|$ determination from superallowed nuclear β decay, the status and the future direction of the $|V_{ud}|$ determination from neutron β decay are discussed.

2. Supperallowed nuclear β decay

A β transition between two $J^{\pi} = 0^{+}$ and $T = 1$ states is of pure vector, and the transition strength is often expressed in terms the so-called "ft" value (phase-space-corrected halflife). With the aforementioned corrections, the "corrected" $\mathscr{F}t$ value is directly related to $|V_{ud}|$ as follows [3]:

$$\mathscr{F}t \equiv ft\left(1+\delta_R'\right)\left[1-(\delta_C-\delta_{NS})\right] = \frac{K}{2\,|V_{ud}|^2\,G_F{}^2\,(1+\Delta_R)}, \tag{2.1}$$

where $K/(\hbar c)^6 = 2\pi^3\hbar\ln 2/(m_e c^2)^5$, δ_C is the isospin-symmetry-breaking correction, Δ_R is the quantum loop correction. δ_R' and δ_{NS} comprise the transition-dependent part of the radiative correction, the former independent of the nuclear structure and the latter nuclear structure dependent. The size of these correction terms is $\delta_R' \sim 1.5\%$, $\delta_C - \delta_{NS} \sim 0.3 - 0.7\%$, and $\Delta_R \sim 2.4\%$.

In 2005, Hardy and Towner published a new survey of world data on superallowed $0^+ \to 0^+$ β decays [3]. In this survey, all previously published measurements were critically reviewed, and more than 125 independent measurements for a dozen or so different transitions that met certain criteria were included in the final analysis. The results showed an excellent consistency of the corrected $\mathscr{F}t$ values among different transitions, confirming the validity of the applied nuclear structure dependent corrections. Since then, eight more publications appeared whose data can be incorporated (see Ref. [4] and references therein). Also, an improved calculation on Δ_R has been published [2]. With these, Hardy obtained an updated value of $|V_{ud}|$ in Ref. [4],

$$|V_{ud}| = 0.97378(27), \tag{2.2}$$

where the breakdown of the contribution to the uncertainty is as follows: ± 0.00018 from Δ_R, ± 0.00015 from the nuclear-structure-dependent corrections, and ± 0.00007 from experimental uncertainties. This value is consistent with the value obtained in Ref. [3].

Currently there is an active experimental program aimed at further testing the nuclear structure dependent corrections and reducing the associated uncertainties. This involves both increasing the precision on the existing $\mathscr{F}t$ values and measuring the $\mathscr{F}t$ values of new transitions.

3. Neutron β decay

In the case of free neutron β decay, knowledge of both neutron lifetime τ_n and the ratio of the axial to vector coupling constant $\lambda = G_A/G_V$ is required to determine G_V.

$$|V_{ud}|^2 = \frac{G_V^2}{G_F^2(1+\Delta_R)} = \frac{2\pi^2}{G_F^2 m_e^5 \tau_n (1+3\lambda^2) f^R (1+\Delta_R)}, \tag{3.1}$$

where Δ_R is the aforementioned quantum loop correction, m_e is the electron mass, f^R is the phase space factor (including the outer radiative correction). Numerically [2],

$$|V_{ud}|^2 = \frac{4908.7(1.9)\text{ s}}{\tau_n(1+3\lambda)}, \tag{3.2}$$

where the uncertainty quoted is from Δ_R.

The value of λ is determined from measurements of decay correlations. The differential decay rate, averaged over electron spin, is given by [6]

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + \langle \boldsymbol{\sigma}_n \rangle \cdot \left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu}\right)\right], \tag{3.3}$$

where m_e is the electron mass, E_e the electron energy, $\boldsymbol{p}_e$ the electron momentum, E_ν the neutrino energy, $\boldsymbol{p}_\nu$ the neutrino momentum, and σ_n the neutron spin. Coefficients a, A, and B depend only on λ in the SM. Among them, A is the most sensitive to λ with $\frac{d\lambda}{dA} = 2.6$. a has a similar but slightly reduced sensitivity to λ with $\frac{d\lambda}{da} = 3.3$. B is much less sensitive to λ with $\frac{d\lambda}{dB} = 13.4$. So far, the determination of λ from free neutron decay has been provided by measurements of A. The uncertainty in λ from the most precise measurement of a [7] is more than ten times larger than the uncertainty in λ from the most precise measurement of A [8].

The current experimental situation is graphically summarized in Fig. 1. The precision with which the recent four measurements [8, 9, 10, 11] determined the value of A ($0.6 - 1.6\%$) is not sufficient to make a determination of $|V_{ud}|$ from neutron β decay with a precision comparable to that from nuclear β decay. Furthermore, the agreement among the four measurements is poor. In addition, the recent neutron lifetime measurement [13] differs from the average of previous experiments [12] significantly (see Fig. 2). Clearly new measurements of A with a higher precision are warranted. Also new lifetime measurements are needed to settle the unsatisfactory situation with the neutron lifetime[1].

3.1 Asymmetry measurement

A typical experimental arrangement for A coefficient measurements involves measuring the forward-backward asymmetry of electron emission with respect to the neutron spin in polarized neutron β decay. Polarized neutrons (a beam of cold neutrons in almost all cases) are let decay in a decay volume and electrons from the neutron decay are guided by a strong magnetic field towards one of the two electron detectors located at the ends of the decay volume. When the detectors have a 4π coverage of β decay events, the asymmetry in the count rate in the two detectors can be related to the A coefficient as follows:

$$A_{\rm exp}(E_e) = \frac{N_1(E_e) - N_2(E_e)}{N_1(E_e) + N_2(E_e)} = \frac{1}{2}PA\beta, \tag{3.4}$$

where E_e is the electron's energy, $N_{1(2)}$ is the count rate in detector 1(2), P is the average polarization of the neutrons, and β is the velocity of the electron in the units of the velocity of light.

Three major sources of systematic uncertainties can be identified in the previous experiments. They are (1) neutron polarization determination, (2) background, and (3) detector effects including backscattering of β particles. As evident from Eq. 3.4, the polarization determination has to be done to a precision better than the precision to which A is to be determined. Also, incomplete

[1] Note that similar sudden jumps in the measured values of particle properties have been observed many times (see e.g. the history plots in Ref. [12]). Therefore a measurement cannot be dismissed simply because it is significantly different from the average of previous measurements.

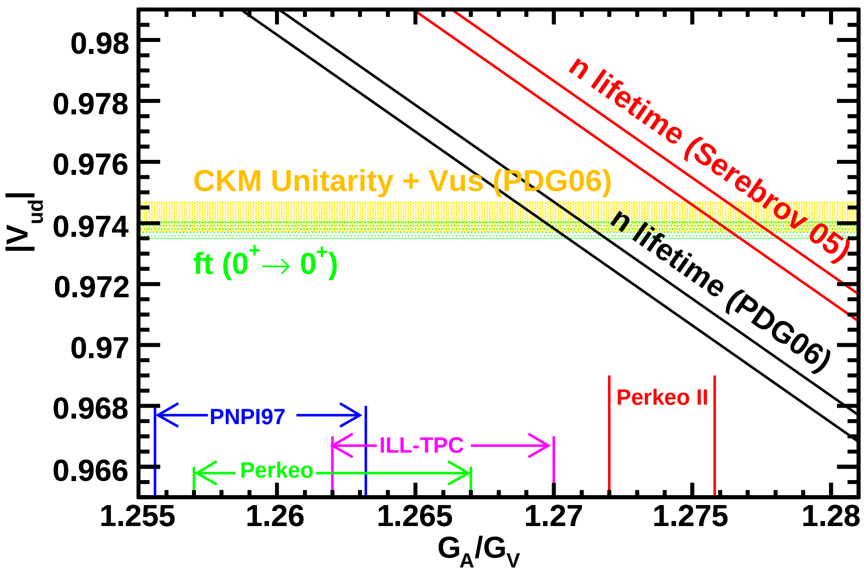

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Figure 1: The current experimental status of the determination of $|V_{ud}|$. The values of $\lambda(=G_A/G_V)$ from the four recent measurements are shown by four brackets along the λ axis as well as the constraints from the world average of the neutron lifetime measurements as given by the Particle Data Group [12] and a recent measurement given by Ref. [13]. (Note that the average given by the Particle Data Group [12] does not include the recent measurement reported in Ref. [13].) The combination of a λ measurement and the neutron lifetime measurement determines the value of $|V_{ud}|$. Also shown are the $|V_{ud}|$ determination from nuclear β decay and the $|V_{ud}|$ determination from kaon and B-meson decays and the assumption of CKM unitarity.

knowledge of the background signal will lead to an erroneous determination of $N_{1(2)}$, thereby giving an erroneous determination of A. With regard to the detector effects, due to the small end point energy of the electron spectrum ($E_e^0 = 782$ keV), a significant fraction ($\sim 10\%$ for plastic scintillation counters) of electrons from neutron β decay directed to one detector can backscatter from the surface of the detector and are detected by the other detector. A non-negligible fraction of the backscattered electrons leave undetectably small energy deposition in the first detector, hence introducing an error in the asymmetry determination. (These electrons are called missed backscattered electrons.) Understanding the backscattering of low energy electrons and properly characterizing the detector response is clearly of vital importance.

In order to address the unsatisfactory situation represented in Fig. 1, measurements of A with a precision of $\delta A/A = 0.2\%$ or better are required (The uncertainty reported in Ref. [8] (PerkeoII experiment) is $\delta A/A = 0.6\%$). Clearly, these measurements need to address the above-mentioned systematic issues. In Table 1, major systematic corrections applied to the results of the recent four measurements are listed. It is seen that corrections that are significantly larger than the reported uncertainty were applied. Experiments with low background, high polarization ($> 99.9\%$), and small detector effects are highly desirable since they do not require large corrections, thus improving the

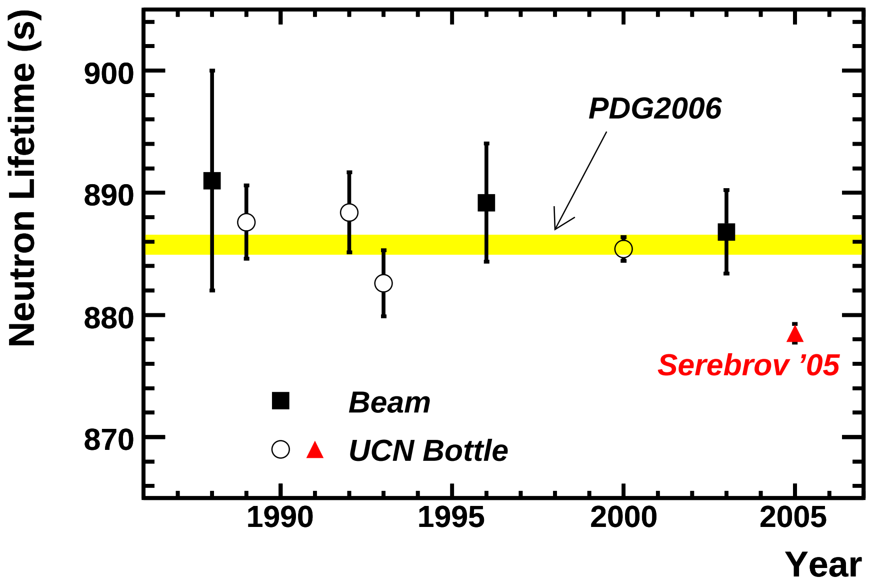

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Figure 2: Recent neutron lifetime measurements. Data points are taken from Refs. [13, 14, 15, 16, 17, 18, 19, 20]

Table 1: Major systematic correction in the recent *A* measurements

Experiment	*A*	Systematic corrections	
		Polarization	Background
Perkeo (1986)	-0.1146(19)	2.6%	3%
PNPI (1991)	-0.1116(14)	27%	small
ILL-TPC (1995)	-0.1160(15)	1.9%	3%
Perkeo II (2002)	-0.1189(7)	1.1%	0.5%[2]

reliability of systematic error assignment.

There are in fact several experiments ongoing or planned to measure *A* with a higher precision.

Since their last publication [8], Perkeo II collaboration have implemented some upgrades, including a new ballistic supermirror guide for a higher neutron flux [21] and a new crossed supermirror polarizers for a higher neutron polarization [22]. At the same time, a new experiment Perkeo III has been developed.

There are two major efforts under way to measure *A* in US. The UCNA experiment [23], currently being commissioned at Los Alamos National Laboratory, aims at a 0.2% measurement of *A* using ultracold neutrons (UCNs)[3]. UCNs are produced in a spallation driven solid deuterium

[3] Ultracold neutrons are neutrons with total kinetic energy less than the effective potential U_F presented by a material

source [24]. The use of UCNs from a pulsed spallation source has two major advantages, i.e, high polarization and low background. The UCNs are then sent through a polarizer/spin flipper, and introduced into a decay volume. The wall of the decay volume is a 3 m-long diamond coated quartz cylinder 10 cm in diameter. The decay volume is in the warm bore of a superconducting solenoidal magnet, which provides a holding field of 1 T. The decay electrons spiral along the magnetic field lines towards one of the detectors, which are a combination of a wire chamber [25] and a plastic scintillator. The use of a thin wire chamber in front of a plastic scintillator will help reduce the missed backscattered electrons. In addition, detailed studies of low energy electron backscattering were performed [26] to help build a reliable model of missed backscattered events, which is necessary in applying a small correction due to the missed backscattered events to the final results. Furthermore, a small spectrometer was built to provide a monoenergetic electron beam for off-line calibration of the detector system [27].

The abBA collaboration proposes to perform a simultaneous measurements of a, A, B, and the Fierz interference term b (which is zero in the SM) at the Spallation Neutron Source (SNS) [28]. The goal of the abBA experiment is to determine a, A, B, and b with an absolute precision of $\sim 10^{-4}$. In order to address known problems in previous experiments, the abBA experiment includes several new features such as, the use of pulsed neutron source, the use of a polarized helium-3 transmission cell as a neutron polarizer, coincidence detection of the decay electrons and the protons, and the use of segmented silicon detectors. Since in the SM, a, A, and B depends only on λ, the consistency among a, A, and B will provide a powerful check for potential systematics.

There are also efforts to improve the precision of a. The aCORN experiment, being prepared at NIST, aims to determine a to a statistical precision of 1% or less by performing coincidence detection of electrons and recoil protons and selecting two kinematic regions such that a comparison of the rates in the two regions directly yields a measurement of a [29]. The aSPECT experiment, currently being commissioned at Mainz, will measure the recoil proton energy spectrum using a magnetic spectrometer with electrostatic retardation potentials [30]. The expected precision is $\delta a/a = 0.25\%$.

3.2 Lifetime measurement

Traditionally, the neutron lifetime has been measured using one of the two following methods: 1) the beam method and 2) the bottle method. In the beam method, a beam of cold neutrons is introduced into a decay volume, where the number of decays per unit time is measured by counting the decay products (electrons or protons). The lifetime (the inverse of the decay rate) can be determined if the number of neutrons in the decay volume is known. A major difficulty and limiting factor associated with this method is the neutron flux determination (necessary to determine the number of neutrons in the decay volume) because it is difficult to detect cold neutrons with a very well known detection efficiency.

In the bottle method, UCNs are loaded into a material bottle and are stored for a variable length of time before the remaining neutrons are counted. The neutron lifetime is extracted from the dependence of the number of detected neutrons on the storage time. The largest source of

boundary. These neutrons, therefore, can be confined in a material bottle. Typically $U_F \sim 200$ neV, which corresponds to velocities of order 5 m/s, wavelengths of order 500 Å and an effective temperature of order 2 mK.

uncertainty in this method is the interaction of the neutrons with the walls of the storage bottle, which provide additional channel through which the stored neutrons can be lost in addition to the β decay. Most experiments use data to extrapolate to the ideal case of no wall losses, by for example, taking data for different storage volume sizes and extrapolating to an infinite volume.

It is clear that a new method free from these systematics is necessary in order to address the unsatisfactory situation shown in Fig. 2. In fact, in order to overcome these difficulties, a new method in which UCNs are confined in a bottle only by the magnetic force [31] (or the magnetic and the gravitational forces) has been developed in laboratories around the world, including NIST [32, 33], PNIP/ILL [34], Munich [35], and LANL [36]. In such a trap, UCNs do not interact with the walls, and therefore β decay is the only mechanism through which the trapped neutrons can disappear. The storage of UCNs in a magnetic trap has already been demonstrated [33, 34]. It is expected new results from these new experiments will become available very shortly.

4. Summary and outlook

The current determination of the value of $|V_{ud}|$ is provided by supperallowed nuclear β decays, based on measurements of the strength of a dozen or so different transitions. The results are consistent among different transitions, validating the nuclear structure dependent corrections. The current experimental activities are aimed at further testing the nuclear structure dependent corrections and reducing the associated uncertainties, by both increasing the precision on the existing $\mathscr{F}t$ values and measuring the $\mathscr{F}t$ values of new transitions.

Determination of $|V_{ud}|$ from neutron β decay with an improved precision will provide a useful cross check of the current determination of $|V_{ud}|$ from nuclear β decays. Furthermore, precision measurements of neutron decay parameters hold the most promise for a further improvement of the determination of $|V_{ud}|$. Currently there are a number of experiments ongoing and planned that will determine A and a to a relative precision of the order of 0.1%. In addition, there are a number of experiments ongoing and planned to determine the neutron lifetime with magnetically trapped UCNs. With results from these new experiments, determination of $|V_{ud}|$ from neutron β decay with a similar precision to that from nuclear β decays may be possible.

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