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Evaluating V_{ud} from neutron beta decays

Dinko Počanić[*†]
University of Virginia, Charlottesville, VA 22904-4714, USA
E-mail: pocanic@virginia.edu

Although well studied, the neutron still offers a unique laboratory for precise tests of Standard Model (SM) predictions. Neutron decay is free of nuclear structure corrections present in nuclear beta decays, and, with a 10^8 times larger branching ratio than the theoretically cleaner pion beta decay, it is more readily accessible to experimental study than the latter. Measurements at sufficient precision of the neutron lifetime, and of correlations in free neutron beta decay, offer several stringent tests of the SM, including the weak quark couplings (quark-lepton universality), and certain extensions beyond the standard $V-A$ weak interaction theory. This paper focuses on the long-running free neutron beta decay experimental program aimed at obtaining an independent determination of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix element V_{ud}. We discuss the present state of precision achieved in this program and briefly review the currently active projects, as well as the expected near-term improvements in the field.

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1. Motivation

In one form or another, quark-lepton universality has been a prominent pillar of the evolving description of the fundamental interactions in particle and nuclear physics since the 1950s. Its systematic treatment was completed with the introduction of the Cabibbo-Kobayashi-Maskawa mixing matrix [1, 2] which summarizes the flavor-changing processes induced by weak interactions of quarks. Examining the properties of the 3×3 unitary CKM matrix in detail allows us to address a number of questions of considerable interest to mapping the limits of the present Standard Model.

The CKM matrix unitarity is one among these questions. A departure from unitarity would indicate the presence of new physics (a possible 4th fermion generation, additional bosons, or compositeness in the known ones, supersymmetric particles, leptoquarks, etc.). The most precise test of the CKM matrix unitarity is performed in its first row, i.e., by evaluating

$$\Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \,, \tag{1.1}$$

where $|V_{ub}|^2 \simeq 1\times10^{-5}$ is negligible. The most recent global evaluation of the CKM matrix unitarity yields $\Delta = 0.0005(5)$, in excellent agreement with the 3-generation SM prediction [3]. Leaving V_{us} aside, the V_{ud} input is essentially determined by the measurements of rates of several superallowed Fermi (SAF) $0^+ \to 0^+$ nuclear beta decays [4]. SAF decay measurements are carried out with impressive precision; however their interpretation is limited by theoretical uncertainties, which also include the uncertainties related to nuclear structure corrections. While the latter are claimed to be well controlled, an independent experimental determination of V_{ud} in systems not subject to nuclear structure effects would be highly desirable. Two such systems present themselves:

Not involving any baryons, the pion beta decay, $\pi^+ \to \pi^0 \mathrm{e}^+ \nu_\mathrm{e}$ or $\pi_{\mathrm{e}3}$, a pure vector $0^- \to 0^-$ transition, is the theoretically cleanest probe of V_{ud}. It is, however, a rare decay with a branching ratio of $\mathscr{O}(10^{-8})$, which makes high precision measurements extremely challenging.

Incorporating both vector and axial vector amplitudes, neutron beta decay, $\mathrm{n} \to \mathrm{p}\,\mathrm{e}^- \bar{\nu}_\mathrm{e}$, is more complex but experimentally more accessible than $\pi_{\mathrm{e}3}$ decay. This complexity, on the other hand, provides redundant ways to measure the SM-predicted observables, providing independent cross-checks of possible new physics, including tensor interactions, supersymmetric as well as right-handed extensions to SM, etc., with competitive sensitivity [5].

We next turn our attention to precision studies of the neutron beta decay with the express goal to extract the CKM matrix element V_{ud}.

2. Basics of neutron beta decay

With a three-body final state, all beta decays are described by several experimental observables. Since only the vector amplitude is subject to weak interaction universality through vector current conservation, the axial vector contribution complicates the determination of V_{ud} in neutron decay. Thus, unlike SAF and $\pi_{\mathrm{e}3}$ decays, measuring τ_n, the neutron lifetime (or decay rate), is not enough; an additional observable, $\lambda = G_A/G_V$, the ratio of axial vector to vector form factors, has to be measured, as illustrated in Figure 1. Measurements of τ_n and of the ratio λ each present their own challenges, briefly examined below. We close this section with considerations of the

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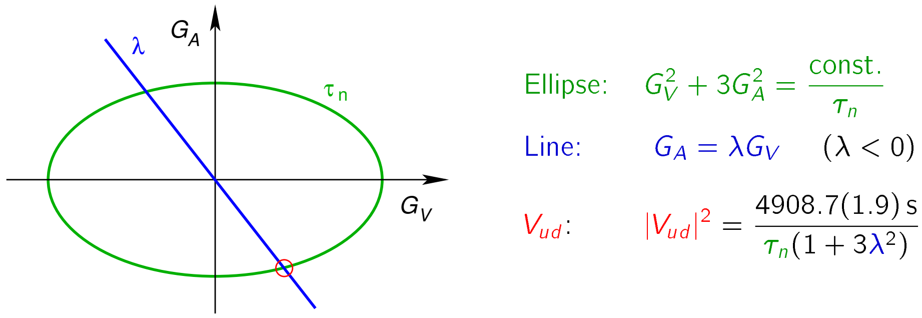

Figure 1: Determination of V_{ud} from neutron decay requires two independent measurements: decay correlations or asymmetry to evaluate the form factor ratio $\lambda = G_A/G_V$, and neutron lifetime or decay rate, $\tau_n^{-1} \propto G_V^2 + 3G_A^2$. The evaluation of $|V_{ud}|$ is illustrated in the (G_V, G_A) parameter plane as the intersection of an ellipse and a line, denoted by a small red circle.

experimental determinations of λ. The standard expression for the differential beta decay rate for particles with spin is given by [6]:

$$\frac{d^5\Gamma}{dE_e\, d^2\Omega_e\, d^2\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \xi \cdot \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + \ldots\right)\right]. \tag{2.1}$$

Here $\vec{p}_e, \vec{p}_\nu, E_e, E_\nu$, are the momenta and energies of the electron and neutrino, respectively, E_0 is the endpoint energy of the electron, and $\vec{\sigma}_n$ is the neutron spin. In the SM, $\xi = G_F^2 V_{ud}^2 (1+3\lambda^2)$, and the key decay observables, a, the neutrino-electron correlation coefficient, A, the beta asymmetry, and B, the neutrino asymmetry, are fully determined by λ, while the Fierz term $b \equiv 0$. Parameters a, A and B provide three independent ways to determine λ; A and a have comparable sensitivities to λ, while B is about $4\times$ less sensitive. In practice, A has been measured much more extensively than a, and it dominates the determination of λ.

3. Current status of V_{ud} from neutron β decay

The neutron lifetime is measured by two methods: (a) counting neutron decays in a fiducial volume containing neutrons (usually from a cold neutron beam), and comparing the result with the number of neutrons present in that same volume (the "beam method"), and (b) storing ultracold neutrons (UCNs) in a bottle, and observing the decay of the number of neutrons with time (the "storage" or "bottle" method). The bottle may be material or magneto-gravitational. In the beam method, the neutron lifetime is measured as $\tau_n = N/r$, where N is the number of neutrons present in the fiducial volume at any time, and r is the rate of the detected decays. Each method comes with its own set of challenges. In the beam method both N and r must be measured absolutely. While the storage method does not require precise knowledge of the detector efficiency, its primary challenge is to account accurately for the loss rate of neutrons to processes other than decay, e.g., capture or up-scattering on walls. Detailed discussion of the techniques and systematics for both methods can be found in recent reviews [5, 7, 8].

The current status of the neutron lifetime measurements is summarized in Figure 2. Two striking features of the results emerge: a strong downward shift over time, brought about by the

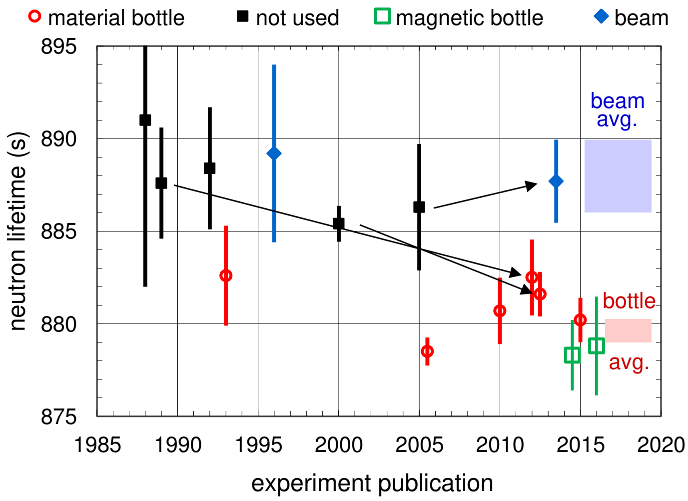

Figure 2: Current status of neutron lifetime measurements; results are shown according to the year of publication. Blue diamonds: beam method measurements [9, 10]. Red circles: material bottle measurements [11, 12, 13, 14, 15, 16]. Green squares: magneto-gravitational trap measurements [17, 18]. Black solid squares: results not used in the global averages, or superseded by subsequent publications. Shaded rectangles on the right denote the beam method average, $\tau_n^{\rm beam} = 888.0 \pm 2.0\,$s (light blue), and the bottle method average, $\tau_n^{\rm bottle} = 879.6 \pm 0.6\,$s (pink). The discrepancy between the two averages exceeds 4σ.

bottle measurements, and the $> 4\sigma$ discrepancy between the storage and beam method experiments. Both methods have recently experienced significant improvements, and new results will be forthcoming. Key unanswered questions concern: (a) the ultimate competitiveness of the beam method, (b) whether or not the above discrepancy will persist, and (c) if so, how the results from the two methods may be reconciled. We next turn our attention to λ.

Figure 3 summarizes the currently available information on the evaluation of $\lambda = G_A/G_V$.

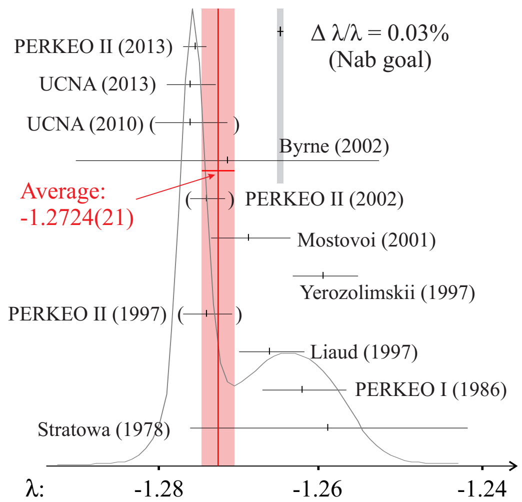

Figure 3: Current ideogram of the values of $\lambda = G_A/G_V$, with the current global average. For more information see, e.g., [5]. The planned precision of the upcoming Nab experiment [21, 5] is also indicated.

experiment	observable	goal uncert.	technique	facility/group
BL2	τ	1 s	cold n beam	NIST
BL3	τ	< 0.3 s	cold n beam	NIST
JPARC τ	τ	< 0.3 s	cold n beam	J-PARC
Gravitrap	τ	0.2 s	UCN/material bottle	PNPI and ILL
Ježov	τ	0.3 s	UCN/magnetic bottle	PNPI and ILL
HOPE	τ	0.5 s	UCN/magnetic bottle	ILL (supertherm. source)
PENELOPE	τ	0.1 s	UCN/magnetic bottle	TU Munich
Mainz	τ	0.2 s	UCN/magnetic bottle	Mainz TRIGA source
UCNτ	τ	$\ll 1$ s	UCN/magnetic bottle	LANSCE UCN source
UCNA	A	0.2%	UCN	LANSCE UCN source
PERKEO III	A	0.19%	cold n beam	MLZ (Munich) and ILL
PERC	A	0.05%	cold n beam	Munich
aCORN	a	$\sim$1%	cold n beam	NIST
aSPECT	a	$\sim$1%	cold n beam	Mainz and ILL
Nab	a	0.1%	cold n beam	SNS

Table 1: Ongoing and planned/funded neutron beta decay measurements, indicating the observable measured, the goal uncertainty level, as well as the general measurement method applied.

Most of the data come from measurements of the β asymmetry in neutron decay; the two measurements of a, by Stratowa (1978) [19] and Byrne (2002) [20] are an order of magnitude less precise. Just as for $\tau_{\rm n}$, there appears to be a gradual drift in the measured values with time, towards greater $|\lambda|$, leading to a poor confidence level for the global average.

Due to the large remaining uncertainties in λ, and to a lesser extent to ambiguities present in the $\tau_{\rm n}$ data, the uncertainty in the value of $V_{ud}^{\rm n} = 0.9758(16)$ exctracted from neutron decay, is significantly greater than that for SAF nuclear β decays, $V_{ud}^{\rm SAF} = 0.97417(21)$, which is dominated by theoretical radiative correction uncertainties. More work is needed to make the neutron result competitive with SAF decays, primarily on λ, although $\tau_{\rm n}$ consistency should also improve.

4. Outlook for the near term

Happily, there is a tremendous amount of activity on ongoing and new precise measurements of the relevant observables in neutron β decay. These experiments are listed in summary form in Table 1. The new BL3 and JPARCτ experiments promise a meaningful comparison of $\tau_{\rm n}^{\rm beam}$ with results from the storage experiments. The latter are in full swing, with the emphasis shifting somewhat toward magneto-gravitational traps. The much needed improvement is also forthcoming for λ, with Nab promising to bring the precision of a to the level comparable to that of A. There is a healthy mix of experimental techniques both in terms of beam (cold vs. UCN) and spectrometer/detector designs, all of it pointing toward significant near-term improvements.

References

[1] N. Cabibbo, *Unitary symmetry and leptonic decays*, *Phys. Rev. Lett.* **10** (1963) 531.

[2] M. Kobayashi and T. Maskawa *CP violation in the renormalizable theory of weak interaction*, *Progr. Theor. Phys.* **49** (1973) 652.

[3] E. Blucher and W.J. Marciano, *V_{ud}, V_{us}, the Cabibbo angle, and CKM unitarity*, in C. Patrignani et al., (Particle Data Group), *Chin. Phys. C* **40** (2016) 100001.

[4] J.C. Hardy and I.S. Towner, *Superallowed* $0^+ \to 0^+$ *nuclear* β *decays*, *Phys. Rev.* C **91** (2015) 025501 [nucl-th/1510.03793].

[5] For a recent review see, e.g., S. Baeßler, J.D. Bowman, S. Penttilä and D. Počanić, *New precision measurements of free neutron beta decay with cold neutrons J. Phys. G: Nucl. Part. Phys.* **41** (2014) 114003 [nucl-ex/1408.4737], and references therein.

[6] J.D. Jackson, S.B. Treiman and H.W. Wyld, *Possible tests of time reversal invariance in beta decay*, *Phys. Rev.* **106** (1957) 517.

[7] A. Young et al., *Beta decay measurements with ultracold neutrons*, *J. Phys. G: Nucl. Part. Phys.* **41** (2014) 114007.

[8] F.E. Wietfeldt and G.L. Greene, *Colloquium: The neutron lifetime*, *Rev. Mod. Phys.*, **83** (2011) 1173.

[9] J. Byrne, P.G. Dawber, C.G. Habeck, S.J. Smidt, J.A. Spain and A.P. Williams, *A revised value for the neutron lifetime measured using a Penning trap*, *EPL (Europhysics Letters)*, **33** (1996) 187.

[10] A.T. Yue et al., *Improved Determination of the Neutron Lifetime*, *Phys. Rev. Lett.* **111** (2013) 222501 [nucl-ex/1309.2623].

[11] W. Mampe et al., *Measuring neutron lifetime by storing ultracold neutrons and detecting inelastically scattered neutrons*, *J. Exp. Theor. Phys. Lett.* **57** (1993) 82.

[12] A. Serebrov et al., *Measurement of the neutron lifetime using a gravitational trap and a low-temperature Fomblin coating*, *Phys. Lett. B* **605** (2005) 72.

[13] A. Pichlmaier, V. Varlamov, K. Schreckenbach and P. Geltenbort, *Neutron lifetime measurement with the UCN trap-in-trap MAMBO II*, *Phys. Lett. B* **693** (2010) 221.

[14] A. Steyerl, J.M. Pendlebury, C. Kaufman, S.S. Malik and A.M. Desai, *Quasielastic scattering in the interaction of ultracold neutrons with a liquid wall and application in a reanalysis of the Mambo I neutron-lifetime experiment*, *Phys. Rev.* C **85** (2012) 065503.

[15] S.S. Arzumanov, L.N. Bondarenko, V.I. Morozov, Yu.N. Panin and S.M. Chernyavsky, *Analysis and correction of the measurement of the neutron lifetime*, *JETP Lett.* **95** (2012) 224.

[16] S.S. Arzumanov et al., *A measurement of the neutron lifetime using the method of storage of ultracold neutrons and detection of inelastically up-scattered neutrons*, *Phys. Lett. B* **745** (2015) 79.

[17] V.F. Ezhov et al., *Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap*, nucl-exp/1412.7434 (2014).

[18] C.L. Morris et al., *A new method for measuring the neutron lifetime using an in situ neutron detector*, nucl-ex/1610.04560 (2016).

[19] C. Stratowa, R. Dobrozemsky and P. Weinzierl, *Ratio of* g_A/g_V *derived from the proton spectrum in free-neutron decay*, *Phys. Rev. D* **18** (1978) 3970.

[20] J. Byrne et al., *Determination of the electron anti-neutrino angular correlation* a_0 *and the parameter* $|\lambda| = |G_A/G_V|$ *in free neutron* β*-decay ... recoil protons in an ion trap*, *J. Phys. G* **28** (2002) 1325.

[21] R. Alarcon et al., *Nab experiment proposal (update)* http://pibeta.phys.virginia.edu/nab_doe_fund_prop.pdf, (2010).