Neutron beta decay in the test of the Unitarity of the CKM matrix

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This is a draft version of a report to be circulated shortly within a broader audience. The purpose is to acquaint the HEP community and the Snowmass process with this research program which is relevant to their mission, although supported from nuclear physics funding sources.

The measurement of observables in free neutron beta decay falls within the broader field of study of the basic properties and symmetries of the electroweak interaction at low energies. Although successful without parallel, the present standard model (SM) of elementary particles and their interactions is known to be incomplete. Additional particles and phenomena must exist. Questions regarding possible extensions of the SM are being simultaneously addressed at the high energy frontier, using particle colliders, and at the precision frontier at lower energies. Neutron beta decay contributes to a precision test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The most precise test of the CKM Unitarity of the CKM matrix is available for the first row:

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

A failure of the CKM Unitarity test signals new physics, e.g., the effects of additional exchange bosons (Refs. [Mar87, Kur00, Ali17] and others), or the existence a fourth quark generation [Mar86, Lan88]. Refs. [Cir10, Gon19] show in an effective field theory (EFT) framework that this test is sensitive to physics beyond the reach of LHC.

The most precise determination of V_{ud} is presently available from the analysis of superallowed beta decays. Here, the $\mathcal{F}t$ values (that is: "phase space factor"×"(partial) half-life" ×"nuclear structure and radiative corrections") of nuclear decays for multiple nuclides are averaged, and are used to determine V_{ud} through [Mar06, HT15]:

$$|V_{ud}|^2 = \frac{2984.43\ \mathrm{s}}{\mathcal{F}t(1+\Delta_V^R)} \qquad (2)$$

The latest analysis of superallowed beta decays from J. Hardy, I. Towner ([HT15, updated in [HT17]) is the one generally adopted. In recent work, C.-Y. Seng, M. Gorchtein et al. recalculated the most controversial part of the radiative correction using dispersion relations, and found it to be substantially larger than previously thought (first, they computed the inner radiative corrections Δ_V^R [Seng 18], and later the nuclear structure-dependent radiative corrections that are part of $\mathcal{F}t$ [Gor19, Seng19]). The updated superallowed beta decay analysis gives $V_{ud} = 0.97366(33)$ [Seng20], or $V_{ud} = 0.97370(14)$ [PDG20]

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(PDG does not use (yet?) the new nuclear structure-dependent radiative corrections which come with larger uncertainties).

For the unitarity test, one needs to combine V_{ud} with determinations of V_{us} and V_{ub}. The contribution of V_{ub} to eq. (1) is small and not controversial. The two most precise types of V_{us} extractions, the ones from K_{l3} decays and from K_{l2} decays, disagree with each other by about 2σ (see [PDG20], which uses data from [FLAG19]). The particle data group summarizes the situation with "One finds an overall 3 sigma deviation from unitarity. That deviation could be due a problem with $|V_{ud}|$ theory (radiative corrections or nuclear physics), the lattice determination of $f_+(0)$ [the form factor for K_{l3} decays, or new physics.". The discrepancy can be reduced up to 1.7σ by including the revised nuclear structure-dependent radiative corrections [Gor19,Seng19], and picking K_{l2} decays as the sole input for V_{us} [Seng20].

Measurements of observables in free neutron beta decay will have an impact on this test. Basing the unitarity test on neutrons (or pions) is desirable due to the absence of nuclear structure-dependent corrections. On the other hand, neutron beta decay shares the sensitivity to the inner radiative corrections Δ_V^R with superallowed (and any other) nuclear decays. With neutron beta decay data, V_{ud} can be determined from measurement of the neutron lifetime, τ_n, and the ratio of the Gamow-Teller and Fermi coupling constants, $\lambda = g_A/g_V$, through:

$$|V_{ud}|^2 = \frac{5024.7\ \mathrm{s}}{\tau_n(1+3\lambda^2)(1+\Delta_V^R)} \tag{3}$$

The Particle Data Group [PDG20] gives the current average lifetime $\tau_n = 879.4(6)$ s, but notes the long-standing disagreement between in-beam and UCN results. To be competitive, the neutron community must reduce the uncertainty in the neutron lifetime to $\tau_n < 0.4$ s. At the same time, measurements of correlation coefficients in neutron beta decays are used to determine λ, and the goal to be competitive is $\Delta\lambda/\lambda < 3.5 \cdot 10^{-4}$. The Particle Data group averages existing experimental results to $\lambda = -1.2756(13)$ [PDG20]. Analysis of neutron beta decay gives a value for V_{ud} consistent with the one from superallowed beta decay, but with lower central value and lesser accuracy. There are multiple experiments under construction that attempt to at least reach the desired precision, an uncertainty of $0.4\ s$, and to resolve the disagreement between the results of two different methods to determine the lifetime [Gre16]. In the US, these are UCNTau collaboration [Pat19], and at BL2/3 at NIST [Wiet14], and a dedicated experiment to understand the disagreement, UCNProBe [Tang19]. Improvements in the determination of λ are expected from the Nab collaboration ([Fry19]), and from the PERC collaboration (Ref. [Dub08, Wang19]), and both are at the desired level of precision or better. The outcome of this program is not only a test of the CKM Unitarity with the absence of uncertainties due to nuclear corrections. The result can also be interpreted as a test of the CVC hypothesis [Dub11], and as a verification of the new radiative corrections.

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