High Precision Neutron Beta-Decay Measurements

Beta-decay studies provide a remarkable tool to probe the helicity structure and quark-lepton universality of the electroweak interaction, providing model independent constraints on the effective new physics energy scale in the multi-TeV range. Measurements of neutron beta-decay also provide basic parameters for the charged weak current of the nucleon.[1] In particular, neutron beta-decay measurements are the definitive source for \( g_A \), the axial form factor, and provide a nuclear-structure-independent value for \( V_{ud} \), the CKM matrix element associated with ud quark currents. Although at present the \( 0^+ \rightarrow 0^+ \) superallowed decays provide the most precise value for \( V_{ud} \), the experimental data for the neutron continues to improve, and should become directly competitive with \( 0^+ \rightarrow 0^+ \) during the next ten years.

We note that \( g_A \) is important in our understanding of the spin and flavor structure of the nucleon\[2, 3\], a central target for high precision lattice QCD studies\[4, 5\], an essential parameter for effective field theories\[6\], and one of a small set of parameters necessary in establishing high precision predictions of solar fusion\[7\]. The neutron lifetime figures prominently in high precision predictions for big bang nucleo-synthesis as well\[8\]. High precision values for \( g_A \) are also important for the reactor neutrino-anomaly question, one of the results driving current interest in short baseline oscillations studies\[9\]. The current value of \( g_A \) is \( g_A = 1.2701(25) \).[10]

High precision neutron beta-decay studies also provide constraints on a large variety of extensions to the standard model. The most stringent constraints come through tests of the quark-lepton universality of the weak interaction, which within the standard model are equivalent to tests of the unitarity of the CKM quark mixing matrix. The strongest constraints come through unitarity tests on the first row: \( V^2_{ud} + V^2_{us} + V^2_{ub} = 0.9999(6) \).[10] For any such test, the diagonal element dominates the sum, and a very high precision (< 0.02%) determination of this diagonal element (\( V_{ud} \) for unitarity tests of the first row of the CKM matrix) is necessary for a competitive unitarity constraint. Here beta-decay also provides the highest precision measurement of a diagonal CKM element, with the value extracted from \( 0^+ \rightarrow 0^+ \) decay being \( V_{ud} = 0.97425(22) \), and with the uncertainties from \( V_{ud} \) and \( V_{us} \) now contributing equally to the sum.[10]

The resultant constraints on (V,A) current interactions are quite stringent, with generic limits on the effective scale for new physics at roughly the 10 TeV level.[11] A large assortment of extensions to the standard model, including new Z' gauge bosons, generic Kaluza-Klein W* excitations, and charged Higgs bosons, are tightly constrained by the unitarity sum.[12] Flavor universality in supersymmetric extensions of the standard model are also constrained by the unitarity sum.[13] The robustness of these limits and enormous progress made in the Kaon-sector in the precision and reliability with which \( V_{us} \) can be determined motivate continued effort on the experimental extraction of \( V_{ud} \).[12] At present, the precision of \( V_{ud} \) from \( 0^+ \rightarrow 0^+ \) decays is nominally limited by loop-level electroweak radiative corrections\[14, 15\], however the nuclear structure dependent corrections for the \( 0^+ \rightarrow 0^+ \) systems remain an area of active concern. Neutron beta-decay can provide a structure-independent value for \( V_{ud} \), a significant contribution to the status of the current unitarity test.

The observables in neutron decay include a number of correlations (and the Fierz term, which influences the energy dependence of the total beta-decay rate) that provide multiple probes of non V-A interactions generated by standard model extensions.[1, 16] For example, constraints on (S,T) interactions arise from angular correlations measurements such as the neutrino-asymmetry and the Fierz term. Because two observables with similar sensitivities to these terms are available, there is a consistency test within the neutron decay system itself for these effects. In particular, it is the aim of some beta-decay experiments (in the planning or construction phase at present) to reach sensitivities of a few parts in \( 10^{-4} \). In this case, the model-independent constraints for interactions...
which only couple to electrons and induce scalar and tensor terms can be made quite stringent with next generation beta-decay experiments. For example, limits in the 5-10 TeV range which are significantly stronger than expected LHC limits are expected to be feasible. In addition, if a new particle resonance is discovered at the LHC, beta-decay experiments at this level of precision may provide complementary information on the quantum numbers and weak couplings of such a resonance, as was recently demonstrated for the case of a scalar resonance[17]. Relevant limits (complementary to those placed by LHC) can also be placed on supersymmetric couplings[18] and couplings to leptoquarks[19].

T-noninvariant angular correlations can also be probed in beta-decay. These experiments can provide constraints on CP violating phases beyond the standard model that are complementary to the ones derived from EDMs.[20, 21] In particular, a number of measurements have been performed of angular correlations proportional to complex, (V,A)couplings (parameterized by the "D" coefficient), with the ongoing work of the emiT[22] and TRINE[23] collaborations having established the basis for pushing sensitivities for T-violating phases to the final state effect level ($10^{-5}$ level).

The past ten years have seen significant growth in the number of physicists involved in neutron beta-decay measurements. Although it is beyond the scope of this brief summary to catalog all of the experimental activity in this subfield, it is characterized by often complementary experiments with cold and ultracold neutrons and has seen the emergence of precision measurements of radiative decay of the neutron [24] for the first time. A number of experiments are underway which target precisions near or at the 0.1% level in the next few years for the lifetime[25], the electron-neutrino-asymmetry[26, 27] and the beta-asymmetry[28, 29]. Taken as a group, they provide a powerful consistency test for the form factors and standard model constraints which can be extracted at this level of precision[30].

Ongoing measurements have also set the stage for a number of ambitious experiments under development or construction which target precisions in the $10^{-4}$ range. For ultracold neutrons, for example, there are lifetime experiments based on material and magnetic trapping geometries[31, 32] and angular correlation experiments under development particularly sensitive to (S,T) interactions[34]. For angular correlations measurements with cold neutron beams, the PERC[35] collaboration based in Munich have as their goal polarimetry and other systematic errors ultimately in the low $10^{-4}$ range, and the Nab/ABba[36, 37] collaboration will be targeting systematic uncertainties below the $10^{-3}$ level for their measurements as well.

Intensity frontier development should provide the opportunity to optimize existing cold neutron beams delivery for fundamental neutron physics research, positively impacting beta-decay experiments as well as a variety of other fundamental neutron studies. For ultracold neutron-based experiments, the intensity frontier initiative could provide the opportunity to construct a next-generation source of extracted ultracold neutrons. Although work over the past ten years has established viable strategies to significantly increase ultracold neutron densities, experiments remain strongly constrained by the ultracold neutron densities at existing sources. A next-generation source could permit the community to capitalize on the ongoing refinement of systematic errors in existing beta-decay, EDM and short-range interaction searches. In particular, for beta-decay studies, it should enable the next generation of beta-decay experiments with ultracold neutrons to reach sensitivities limited by systematic errors, and probe energy scales comparable to and in some cases above that planned for the LHC.