Neutrinoless Double Beta Decay

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The search for neutrinoless double beta decay ($0\nu\beta\beta$) is among the highest priorities in Nuclear Physics. The goal of this program is to determine whether the Lepton Number is a globally conserved quantity, and whether neutrinos are Dirac or Majorana particles. Dirac neutrinos would require the promotion of the accidental, global symmetry of lepton number to something fundamental, making matter and antimatter intrinsically different. Majorana neutrinos would directly point toward a deeper theory and connect our low-energy world with mass scales that would otherwise be inaccessible. A creative era in which many distinct approaches to this search are being taken is now underway, with US playing the leadership role. The next milestone in this quest is the development of at least one US-led experiment with the isotopic mass of order one ton, which will have the sensitivity to discover Majorana neutrinos with the mass as low as 10-15 meV. Development of such an ambitious program is both timely and scientifically relevant.

I. EXECUTIVE SUMMARY

The question of whether neutrinos violate Lepton Number conservation is among the biggest outstanding challenges in nuclear and particle physics. The question is not only relevant to our understanding of neutrinos themselves, but to astrophysics, to physics at the highest mass scales, and perhaps even to our understanding of the origin of nuclear matter. Our view of neutrinos has changed dramatically over the past decade or so, as results from atmospheric, solar, reactor, and accelerator-based neutrino oscillation experiments provided compelling evidence that neutrinos change flavor and that this transformation occurs because they are massive and mixed.

It may seem that such a discovery would modify the Standard Model of nuclear and particle physics only modestly. Massive neutrinos would appear in nature just like every other known fermion, through the mechanism of electroweak symmetry breaking. However, such a description poses challenges of its own. It is fair to say that we do not fully understand the neutrino mass.

Perhaps the most straightforward way to include massive neutrinos in the Standard Model Lagrangian is to indeed treat them as we do other "Dirac" fermions, giving them mass terms through couplings to the Higgs field. But in doing so we immediately run into problems. The first is that a Dirac mass term by its very nature requires a chirally right-handed neutrino, ν_R and a left-handed antineutrino, $\bar{\nu}_L$ (increasing the number of neutrino states from two to four). As electroweak singlets, however, these additional neutrino states have no function in the model other than to allow neutrinos to be massive. They participate in no interactions other than their coupling to the Higgs bosons and gravity, and both of those interactions are minuscule on microscopic scales. A ν_R is essentially a sterile state. Even worse, while a ν_R is an electroweak singlet and a $\bar{\nu}_R$ is part of a doublet, there is no fundamental difference between them: there is no known gauge symmetry that distinguishes these states. That makes neutrinos very different that the electrically charged fermions, such as electron and positron. The ν_R and $\bar{\nu}_R$ are both right-handed, neutral, spin-1/2 particles with the same mass. To force them to be different we must promote the global—and otherwise completely accidental—symmetry of Lepton Number, which formally distinguishes leptons from antileptons, to something fundamental. If neutrinos are Dirac fermions, matter and antimatter are *fundamentally* different — a startling realization. To date, conservation of Lepton Number is nothing more than an empirical law.

A different way of including neutrinos into the Standard Model is to assume that there are indeed just two states—ν_L and ν_R—and that the interactions that appear to proceed via "antineutrinos" are those in which the right-handed chiral state participates. Under such description, neutrinos are therefore their own antiparticles ("Majorana fermions"), and interactions in which lepton number was violated could occur. (Another global symmetry now known to be violated is lepton flavor number: neutrino flavor transformation clearly violates this symmetry). This description is not without issues, however. The simplest Lagrangian mass term that includes neutrinos as Majorana particles has dimension 5 and is not renormalizable. Like the early Fermi theory of β decay, such a term points very clearly toward a deeper, more complete high-energy theory.

Majorana neutrinos have several intriguing and important consequences. A natural way of explaining the tiny observed neutrino masses is via the "see-saw" mechanism for Majorana neutrinos, where the observed mass of the neutrino comes from the ratio of Dirac fermion masses to Majorana states with extremely high mass. Small values of the neutrino masses point to the mass scales in the Great Unification range, something unlikely to be probed by terrestrial accelerators. Thus, Majorana neutrinos may be our only window to the highest energy scales.

Majorana neutrinos may also violate CP symmetry in new ways, and in so doing help explain the preponderance of nuclear matter over antimatter in the early Universe through the mechanism of 'leptogenesis". Therefore, the discovery of Majorana neutrinos would have profound theoretical implications in the formulation of a new Standard Model, while yielding insights into the origin of mass itself.

The only practical way of determining whether neutrinos are Majorana fermions is by observing the process of neutrinoless double beta decay ($0\nu\beta\beta$), a process that explicitly violates lepton number. The rate at which such a process happens depends on the neutrino masses themselves, the sizes of the mixing angles and possible CP-violating phases, the nuclear matrix elements and phase space of the particular reaction being studied and, of course, whether neutrinos are Majorana particles or not.

Several high level studies such as the 2004 APS Multi-Divisional Neutrino Study, the 2005 NuSAG report, the 2006 EPP 2010 study, conducted by the National Academy of Sciences, and the 2007 Nuclear Physics Long Range Plan identified the investigation of neutrinoless double beta decay as one of the core areas of interest of the nuclear and particle physics communities. It is clear that $0\nu\beta\beta$ experiments sensitive at least to the mass scale indicated by the atmospheric neutrino oscillation results are needed.

For $0\nu\beta\beta$ decay the summed energy of the emitted electrons produces a monochromatic peak at the Q-value of the decay. Observation of a peak at the $\beta\beta$ endpoint would thus quantify the $0\nu\beta\beta$ decay rate, demonstrate that neutrinos are Majorana particles, indicate that lepton number is not conserved, and, combined with nuclear structure calculations, provide a measure of the effective (average) Majorana mass, $\langle m_{\beta\beta}\rangle$, of the electron neutrino. There is consensus within the neutrino physics community that such a decay peak would have to be observed for at least two

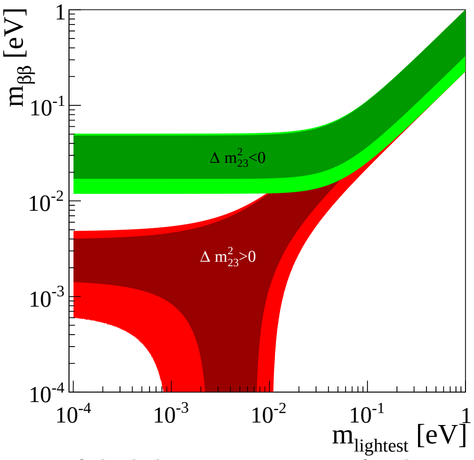

FIG. 1: Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted and normal hierarchies. The dark shaded regions correspond to the best-fit neutrino mixing parameters and account for the degeneracy due to the unknown Majorana phases. The lighter shading corresponds to the maximal allowed regions including mixing parameter uncertainties. The green region labeled $\Delta m^2_{23} < 0$ corresponds to the so-called inverted neutrino mass hierarchy. The red region $\Delta m^2_{23} > 0$ is the so-called normal mass hierarchy.

different decaying isotopes at two different energies to make a credible claim for $0\nu\beta\beta$ decay. Neutrino oscillation experiments indicate that at least one neutrino has a mass of $\sim$ 45 meV or more. As a result and as shown in Figure 1, in the "inverted hierarchy" mass spectrum with $m_3 = 0$ meV, $\langle m_{\beta\beta}\rangle$ is between 10 and 55 meV depending on the values of the Majorana phases and the elements of the neutrino mixing matrix. This is sometimes also referred to as the atmospheric mass scale. Exploring this region requires a sensitivity to half-life exceeding 10^{27} years. This is a challenging goal requiring several tonne-years of exposure and very low backgrounds.

We live in an exciting era for neutrinoless double-beta decay. The high importance of the question has led to an explosion of creativity in the low-background precision experimentation. Many different technologies and approaches have been developed to search for $0\nu\beta\beta$, and most of them are now coming to fruition in the form of the current-generation $0\nu\beta\beta$ experiments. US physicists play key roles in most of these developments. Each of these approaches has its advantages and its challenges. The recent NSAC Neutrinoless Double Beta Decay sub-panel summarized the characteristics of the "ideal" $0\nu\beta\beta$ experiment, and each of the approaches currently being pursued is typically strong in some of these characteristics, and weaker in others. The technical developments associated with the pursuit of $0\nu\beta\beta$ are themselves great achievements: from the creation of ultra-pure materials, to novel tracking devices, to new event reconstruction algorithms. We expect that the next 2-3 years, with existing detectors continuing to run and new detectors coming on-line, will be particularly exciting. It will then be both timely and scientifically relevant to pursue the next-generation goal of developing at least one, or several experiments with the ultimate goal of discovering Majorana neutrinos if they exist in the inverted hierarchy range.

It is our belief that the search for neutrinoless double beta decay is an extremely high priority for the nuclear physics community.