Next Generation Neutrinoless Double β-Decay Experiments

Andreas Piepke, R.G. Hamish Robertson

The matter asymmetry of the universe remains one of the deepest mysteries in physics. The absence of significant amounts of antimatter requires, as Sakharov explained, a time when the universe was not in equilibrium, the non-conservation of baryon and lepton number, and violation of CP invariance. Non-conservation of baryon and lepton number has not been experimentally discovered, despite heroic efforts to observe proton decay. Violation of CP in the quark sector is well established but is insufficient to explain the asymmetry. As a consequence, it is essential to explore new sources of CP violation, and searches for static electric dipole moments and neutrinoless double β-decay are high priorities in nuclear physics. The observation of neutrinoless double β-decay would demonstrate the non-conservation of lepton number, and by inference the non-conservation of baryon number.

In contrast to all other fundamental building blocks of matter neutrinos carry no electrical charge, opening the possibility that they are their own antiparticles if no conserved quantum number forbids it. The experimental demonstration of neutrino oscillations shows that neutrinos have mass, and therefore that neutrinoless double β-decay can occur. Such a process would violate lepton number conservation.

The 2007 Nuclear Science Long Range Plan recognized this scientific opportunity and called next generation experimental searches for this effect one of "Two highlights of this ambitious program...". The Long Range Plan further states: "... neutrinoless double beta decay experiments could determine whether the neutrino is its own anti-particle, and therefore whether nature violates the conservation of total lepton number: a symmetry of the Standard Model whose violation might hold the key to the predominance of matter over antimatter in the universe." In this area nuclear physics can, thus, provide profound insights into the inner symmetries of matter, independent of and complementary to the LHC.

The rate of neutrinoless double β-decay ($0\nu\beta\beta$) can be written as:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} \cdot g_A^4 \cdot \left|\frac{\langle m_{ee}\rangle}{m_e}\right|^2 \cdot |M_{0\nu}|^2 \qquad (1)$$

where $G_{0\nu}$ is the phase space factor, $M_{0\nu}$ is the nuclear matrix element, and the effective Majorana mass is:

$$\langle m_{ee}\rangle = \left|U_{e1}^2 \cdot m_1 + U_{e2}^2 \cdot m_2 \cdot e^{i\alpha} + U_{e3}^2 \cdot m_3 \cdot e^{i\beta}\right|. \qquad (2)$$

The effective Majorana mass is a coherent sum over mass eigenstates with (potentially) CP-violating phases, and cancellations can occur. It can also be modified by interference with other hypothesized non-standard-model processes. The combination of neutrino oscillation data and the light neutrino exchange dominance hypothesis allows the computation of ranges of values for the effective Majorana mass, Eq. 2, for the degenerate, inverse-hierarchy, or normal-hierarchy neutrino mass scenarios.

Experimental searches for $0\nu\beta\beta$-decay state their observations in terms of $T^{0\nu}_{1/2}$ or a limit for it. As can be seen from Eq. 1, theoretically calculated phase space factors and nuclear matrix elements are required to convert an experiment-dependent observable into a relevant physics quantity such as the effective Majorana mass. There has been consensus that the calculation of $G_{0\nu}$ is essentially exact, although some recent work [1] has challenged this notion. Nuclear structure calculations of $M_{0\nu}$, using different methods (see e.g. [2] for a compilation), give rather different values for the matrix elements. For a given effective Majorana neutrino mass (common to all double β-decay experiments) the nuclear-model induced variations in the half-life, the experimentally observable quantity, are typically of order a factor 5. Further theoretical progress in the computation of nuclear matrix elements would clearly be a huge benefit for this field. This should include an improved understanding of how to accommodate β-quenching (which value of g_A to use) as g_A enters in the fourth power into calculated rates. Substantial renormalization is needed in some models to fit $2\nu\beta\beta$ rates [3].

Oscillation data indicate that double β-decay searches with mass sensitivities of about 50 meV and 15 meV are needed to cover the degenerate or inverse-hierarchy scenarios, respectively [4]. Because of the possibility of destructive interference there is no lower limit in the normal hierarchy.

There has been a worldwide response to this scientific challenge, as for the first time there is a more-or-less well defined target for planning new double β-decay searches, modulo the theoretical nuclear physics uncertainties. Researchers are developing experiments considering nine different double β-unstable nuclides. Experiments using large amounts of ^{76}Ge, ^{130}Te, ^{136}Xe, ^{150}Nd are actively being prepared or planned by international teams involving US researchers. A fundamental requirement is that, independent of technical issues concerning background, resolution, scalability etc., there must be sufficient signal to detect. The current generation of double β-decay experiments has been set up to explore the degenerate mass scenario an order of magnitude below the current laboratory limits for the kinematic mass, 2.2 eV. These experiments will definitively address an existing claim of observation in this region [5]. However, if no signal is seen, then ton-scale experiments will be needed to have some chance for a sufficient signal to be detected. Given the possibilities for cancellations in the effective Majorana mass, limit results do not by themselves yield definitive information on the mass ordering and Majorana or Dirac character of neutrinos, but could do so if independent information about the kinematic mass becomes available from experiments such as KATRIN, or from cosmology.

The experience gained with the current generation of 100-kg scale detectors will provide the basis for a technical down-select to a higher detector mass. A half-life limit, to be obtained after a counting time of t years, depends on a number of factors that are under the experimentalist's control:

$$T^{0\nu}_{1/2} \;>\; 333\frac{\alpha\varepsilon}{f}\frac{N_A}{A}\sqrt{\frac{mt}{B\sigma}}, \tag{3}$$

where α denotes the isotope fraction, ε the electron detection efficiency, f a tabulated constant of order unity depending on the confidence level of the limit, N_A Avogadro's number, A (in g/mole) the molar mass of the decaying isotope, m the active mass of the detector in kg, B the detector background in counts keV^{-1} y^{-1} kg^{-1}, and σ the detector energy resolution in keV. Among the many considerations that will influence the final decision would be the cost, redundant identification capabilities, background, and resolution. A great deal of progress has been made towards the large-scale double beta decay detector that is needed to address the question of lepton number conservation.

References

[1] J. Kotila, F. Iachello, Phys. Rev. C 85 (2012) 034316.

[2] A. Dueck, W. Rodejohann, K. Zuber, Phys. Rev. D 83 (2011) 113010.

[3] J. Barea, J. Kotila, F. Iachello, Phys. Rev. Lett. 109 (2012) 042501.

[4] W. Rodejohann, http://arxiv.org/pdf/1206.2560.pdf (2012).

[5] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, Mod. Phys. Lett. A 21 (2006) 1547.