Neutrino-less double beta decay
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Science opportunities

The solar and atmospheric neutrino experiments indicate that neutrinos undergo flavor oscillation and therefore have mass. This indication that neutrinos are massive points to physics beyond the Standard Model and has increased interest in investigating their intrinsic properties. Double-beta decay is a process that probes presently unknown neutrino properties.

Ordinary beta decay of many heavy even-even nuclei is energetically forbidden. However, a process in which a nucleus changes its atomic number by two while simultaneously emitting two beta particles and two anti-neutrinos ($2\nu\beta\beta$) is energetically possible for some even-even nuclei. Such two-neutrino double-beta decay is an allowed second-order weak process that occurs in nature, although its rate is extremely low. Half-lives of $\sim 10^{19}$ years or longer have been measured in several nuclei for this decay mode.

A more interesting process, from neutrino physics point-of-view, is zero-neutrino double-beta decay ($0\nu\beta\beta$) where no neutrino is emitted. Unlike $2\nu\beta\beta$, $0\nu\beta\beta$ violates lepton number conservation and hence requires physics beyond the Standard Model. One can visualize $0\nu\beta\beta$ as an exchange of a virtual neutrino between two neutrons within the nucleus. In the framework of the SU(2) x U(1) Standard Model of weak interactions, the first neutron emits a right-handed anti-neutrino. However, the second neutron requires the absorption of a left-handed neutrino. In order for this to happen, the neutrino would have to be a massive Majorana particle.

Lepton number (L) is conserved in the Standard Model because neutrinos are assumed to be massless and there is no chirally right-handed neutrino field. The guiding principles for extending the Standard Model to include neutrino mass are the conservation of electroweak isospin and renormalizability, which do not preclude each neutrino mass eigenstate to be identical to its anti-particle, or a ``Majorana" particle. However, L is no longer conserved if neutrinos are Majorana particles. Theoretical models, such as the seesaw mechanism that can explain the smallness of neutrino mass, favor this scenario. Therefore the discovery of Majorana neutrinos would revolutionize our understanding of the origin of mass in the lepton sector and call for the experimental probing of theoretical models beyond the Standard Model. If neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence ordinary matter, of the universe. As of yet, there is no firm experimental evidence to confirm or refute this theoretical prejudice that neutrinos are Majorana particles. Experimental evidence of neutrino-less double-beta decay would definitively establish the Majorana nature of neutrinos and will probe its absolute mass scale. Understanding the neutrino mass generation mechanism, the absolute neutrino mass scale and the neutrino mass spectrum are some of the main focuses of future neutrino experiments. Reactor and accelerator experiments will study other properties of the neutrino and are therefore complementary to double beta decay. It should be emphasized however, that neutrinoless double-beta decay is the only practical technique for determining whether the neutrino is a Majorana particle.

The nuclear and high-energy physics communities have recently stressed the need for $0\nu\beta\beta$ experiments. The scientific motivation for their undertaking has been amply described and strongly endorsed by several recent national reviews including: the 2001-2002 Nuclear Science Advisory Committee's (NSAC) Long Range Plan; the National Research Council's (NRC) 2002 Quarks to Cosmos study, the NRC's Neutrino Facilities Assessment Committee 2003 report; the 2005 American Physical Society's (APS) Multidivisional Joint Study on the Future of Neutrino Physics; a detailed assessment from the Neutrino Scientific Assessment Group (NuSAG), a joint sub-committee formed by the NSAC and the High Energy Physics Advisory Panel (HEPAP) to advise DOE and NSF on specific questions related to the U.S. neutrino physics program issued in September 2005; and the Particle Physics Project Prioritization Panel (P5) HEPAP Subpanel's Particle Physics Roadmap report of October 2006. As examples we quote a few of these reports here.

The APS DNP/DPF/DAP/DPB Joint Study on the Future of Neutrino Physics report gives as its first of three recommendations: "We recommend, as a high priority, a phased program of sensitive searches for neutrino-less nuclear double-beta decay." The NRC Quarks to the Cosmos report listed as one of the top 11 questions:
"What are the masses of the neutrinos, and how have they shaped the evolution of the Universe?" Double-beta decay can provide a measure of the neutrino mass and it is the only practical way to determine if the neutrino is a Majorana particle, a key ingredient to Leptogenesis and the evolution of the Universe. The 2007 DNP LRP recommends: "We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative." The NuSAG committee for $0\nu\beta\beta$ gave as its recommendation: "The Neutrino Scientific Assessment Group recommends that the highest priority for the first phase of a neutrino-less double beta decay program is to support research in two or more neutrino-less double beta decay experiments to explore the region of degenerate neutrino masses ($<m_{\beta\beta}> \sim 100$ meV). The knowledge gained and the technology developed in the first phase should then be used in a second phase to extend the exploration into the inverted hierarchy region of neutrino masses ($<m_{\beta\beta}> \sim 10-20$ meV) with a single experiment." The report specifically mentions CUORE, EXO, and Majorana as the technologies that were most advanced.

These committees recommended that experiments with approximately 100 kg of isotope and sensitive to the degenerate mass scale be constructed as a first step. Such efforts are already under development and DUSEL should plan for a further step in sensitivity: The tonne scale with sensitivity to the inverted hierarchy scale. Tonne-scale experiments are needed regardless of whether $0\nu\beta\beta$ is seen in the smaller experiments. If it isn't seen, more sensitivity is required to reach longer half-lives, whereas if it is seen, larger statistical samples of events will be needed for study of distributions. *To fully exploit the underlying physics, experiments on several isotopes will be required and we endorse at least 2 for consideration for the initial suite of experiments at DUSEL via the S4 process. Below we summarize the case for two efforts we consider ready to develop programs for 1-tonne experiments. In addition to this data requirement, support for nuclear theory pertinent to ββ is also endorsed.*

Roadmap for the 1st suite of experiments

While many searches for 0νββ decay have been performed for more than 50 years, a significant shift in scope has occurred with the new generation of experiments planned for DUSEL. In order to reach Majorana mass sensitivities well below the 100-meV level, source masses at the tonne scale will be required for the initial suite of DUSEL experiments; up approximately 2 orders of magnitude from the kg-scale experiments attempted in the past. As a consequence the requirements in terms of infrastructure, component reliability, organization, isotopic enrichment and financial investment have grown substantially.

Two main features are almost universal for this new breed of detectors:

1) the need for isotopic enrichment on a scale unprecedented for science
2) the requirement for exceedingly small backgrounds. Arguably 0νββ detectors are the cleanest complex devices ever built and the large DUSEL detectors will have to further improve –orders of magnitude- beyond such an advanced state of the art.

The last requirement cannot be overstated as on the one hand the discovery of 0νββ should be as conclusive as possible while, on the other, background-free experiments make the best use of the large investment in separated isotopes.

Over the last several years two very different, extensively studied, techniques have shown technologies presently viable for the development of 0νββ decay experiments at the 1-tonne scale. Both of these programs have a significant US effort within a large international collaboration. Each of them is specifically designed for a particular isotope. These large efforts have built substantial momentum and propose detectors that are well matched to the international landscape, as will be explained below.

a) A detector designed for ^{76}Ge would consist of a large array of Ge-diode detectors, running at cryogenic temperatures and cooled either by immersion in a cryogen or, more conventionally, by using a system of cold fingers. Shielding from external radiation would be provided by the cryogen itself or by separate components external to the main detector assembly. The primary mode of background rejection for such a detector is the superior energy resolution that is common in Ge-diode detectors. In addition, recent R&D has shown that readout segmentation within each detector and among detectors would further improve the rejection of γ-ray events by tagging the multiple-site Compton scatterings.
b) ^{136}Xe can be employed in a large time projection chamber (TPC) optimized for best energy resolution at 2.5 MeV. Both liquid phase and moderate pressure gas detectors are being considered, with the liquid option presently being fielded at a

scale of 200 kg and smaller gas phase prototypes in preparation. While good energy resolution is still required in these detectors to separate the 2νββ decay from the 0ν mode, the possibility of identifying the Ba ion produced in the final state is under study as a particularly powerful background rejection method. If found to be practical, the use of Ba-tagging could open the way to background-free measurements.

Each of these techniques can be presently used to cost, in a preliminary way, a workable 1-tonne experiment. It is also likely that each technique could later lead to a detector with 10 tonnes or more of isotope, with further R&D beyond the time scale for the DUSEL initial suite. Some differences exist in terms of timing, international context, detector technology and, possibly, cost. Xenon is substantially easier and cheaper than Germanium to enrich and, in addition, there is experience with a pilot enrichment of 200 kg of the isotope 136. This production is about an order of magnitude larger than any previous case. For Ge, the capability to enrich at the required rate has been demonstrated, and from a technological perspective, a Ge detector may be considered as the most straight-forward path to a 1-tonne detector. Assuming extrapolations in background suppression are correct (the risk attached to this assumption will be assessed by the MAJORANA demonstrator and the GERDA projects), a 1-tonne Ge detector could probably be designed very soon. The Xenon detector with Ba tagging is clearly the most risky –and, as such, still not completely proven- technology. It is also the avenue that promises the lowest background and scalability to 10 tons. In addition a version of the "conventional" part of the detector, that involving liquid xenon, will soon exist as the largest 0νββ-decay experiment in operation. This detector will be an invaluable test bed for the technology. High-pressure Xe gas detectors, also under development, could also be candidates for the 1-tonne scale. The possibility of using the same enriched xenon in rather different detectors is also an important consideration for a wise management of the community assets. The Ge and Xe options have been pursued in the US, respectively, by the MAJORANA and EXO collaborations. A 1-tonne experiment would reach sensitivities at the inverted hierarchy scale or approximately 25 meV.

EXO is at present a collaboration including 60 scientists and engineers from 12 institutions in the US, Canada, Russia and Switzerland. The group operates as a scientific collaboration with a formal structure similar to that of other large scientific collaborations. Three parallel tracks of research exist within EXO: Ba-tagging R&D, EXO-200 design and construction, and gas phase R&D. Funding for a 1-tonne EXO would be proposed to DOE-HEP and the NSF for the DUSEL initial suite.

MAJORANA is at present a collaboration including about 100 scientists from 18 institutions in the US, Canada, Russia, and Japan. The group also operates as a large scientific collaboration within a formal structure. GERDA is a European collaboration also developing Ge technology for 0νββ. The MAJORANA and GERDA collaborations are coordinating their efforts to prepare for a joint 1-tonne project using Ge detectors. A technology choice between the two shielding schemes of MAJORANA and GERDA is a focus of this joint effort. Funding would be shared by Europe and the US under this model with US funding being proposed to DOE-NP and the NSF initial suite.

Both MAJORANA and EXO are technically ready to cost their detectors before the end of calendar 2008. Engineering and R&D support for both EXO and MAJORANA will be needed between now and 2010 to finalize the 1-tonne designs and, in the EXO case, demonstrate the Ba-tagging technology. Experience gained with EXO-200 and the gas-phase R&D will be invaluable to optimize the design of the 1ton detector. Similarly, the experience gained with the MAJORANA 60-kg demonstrator will be very important in the final design of MAJORANA.

Worldwide, several other experiments are being prepared at the 100-kg scale (in isotopic terms) and, in some cases, plans are in place to proceed to the tonne scale. Examples, at different stages of readiness, include CUORE (using tellurium oxide bolometers), MOON (multi-layer hybrid detectors using ^{100}Mo and/or ^{82}Se), SuperNEMO (tracko-calo detector possibly using neodymium) and SNO+ (also planning to use neodymium in liquid scintillator). While in some future incarnations one or more of these technologies may have an interest in pursuing the 1-tonne scale at DUSEL, that is unlikely for the first suite of experiments.

As the two projects above aggressively tool up with the goal to be part of the first suite of DUSEL experiments, it is important to continue funding R&D for new and developing ideas. At present these include COBRA (^{116}Cd), CANDLES (^{48}Ca) and new ideas presented on alternative schemes using Xe and advanced liquid-scintillator detectors with $\beta\beta$ sources chemically dissolved in them. These small R&D projects will substantially enrich the DUSEL program by developing the ability to study new isotopes, important to understand the $\beta\beta$ mechanism once the decay is observed. Many of these R&D programs will likely require underground space very early-on and hence enrich the scientific environment of the Lab at little additional cost.

Infrastructure requirements at DUSEL

EXO and MAJORANA will both require use of cryogenics. For a 1-tonne scale experiment, a liquid Xe EXO will have a cold mass (170 K) of ~15 tonnes and MAJORANA will have a cold mass of ~1.5 tonnes. The experiments together will probably require the underground availability of several 1000 liters of LN_2 in addition to at least 2 tonnes of LXe. In addition a gas phase EXO would be pressurized at 5 to 20 atm. Both detectors will require un-interruptible power. MAJORANA will require underground electroforming facilities. It is expected that EXO and MAJORANA will require one ~500 m^2 clean room each. Both will require regions of class 100 or better clean room space.

Both experiments will be probably installed at the 4850-ft level or deeper, although, for EXO, background calculations will be finalized after the EXO-200 data is analyzed. The availability of analytical tools (high resolution mass spectroscopy, direct γ spectroscopy, neutron activation analysis) will be an asset for both groups. Measures for Radon control and abatement will be very important for both experiments. This appears likely to be a common theme for many groups at DUSEL and it might be advisable for the lab to plan their facilities accordingly. For instance “low Rn air” from the surface, maybe even from a high tower, could be distributed in some regions of the underground to flush sensitive (and relatively small) regions of the experiments. A competent and thoughtful health and safety program will be essential for safe assembly and running of the detectors.

Finally, both ββ decay experiments require large amounts of separated isotopes (^{136}Xe and ^{76}Ge). Because of the very long lead time for the production of these materials and because of the inescapable role that these two isotopes will have in future neutrino research, it would be a very wise investment for the NSF to start isotopic enrichment for these established, low-risk technologies well before the DUSEL program is finalized. While such a proposition may be challenging from the administrative point of view, it would very substantially enhance the visibility and scientific value of the new lab. Funding of the order of \$5M/year for 4 years (2009-13) would substantially help this process. Because of cosmic ray activation some low-background construction materials require long periods of underground “cooldown” before use. Also in this case stockpiling common materials, such as copper, in the Homestake mine immediately would provide a substantial added-value at a later date. An investment of ~\$500k would buy ~40 tons of copper that would probably suffice for both ββ experiments and, probably other detectors.

Education and Outreach

The traditional education of graduate students and postdocs is a very strong opportunity for double-beta decay. The science is compelling and therefore many young people are excited about research in this field. Thus the field will play a strong role in the education of future scientists. Another attractive feature is that the experiments tend to be smaller in scale and therefore it is possible for a student to achieve an understanding of the entire project and play very significant scientific roles. In terms of outreach to the general public, there are a number of “gee-whiz” topics that can be exploited to teach about radioactivity as well as encourage interest in neutrinos. For example, the extreme low-level of activity of a double-beta decay experiment, even when contrasted with the radioactivity of a human body can be used to dramatize not only the technical prowess of the technology, but also drive home the fact that radioactivity is commonplace.

Talks presented at Town Meeting, Nov. 2-4, 2007:

EXO-200 - Hall (U Maryland)
Xe - Nygren (LBNL)
CUORE - Avignone (U South Carolina)
SuperNEMO - Argyriades (LAL Orsay)
MOON - Ejiri (Osaka)
Full scale EXO - Sinclair (Carleton)
Ge - Wilkerson (U Washington)
COBRA - Krawczynski ()
CANDLES - Kisimoto ()
XAX – Arisaka (UCLA)
Nd in scintillator - Calaprice (Princeton)