Experimental Double-Beta Decay

Steven R. Elliott
LANL, MS H803, Los Alamos, NM 87545

The recent demonstrations of oscillations in the atmospheric and solar neutrino data convincingly indicate that neutrinos do have mass. Those data however, do not tell us the absolute mass scale but only the differences of the square of the neutrino masses. Even so, we now know that at least one neutrino has a mass of about 50 meV or larger. Studies of double-beta decay rates offer hope for determining the absolute mass scale. In particular, zero-neutrino double beta decay (ββ(0ν)) can address the issues of lepton number conservation, the particle-antiparticle nature of the neutrino, and its mass. In fact, the next generation of ββ(0ν) experiments will be sensitive to neutrino masses in the exciting range below 50 meV. An overview of ββ(0ν) and its relation to neutrino mass will be discussed followed by a summary of the major proposed experiments.

1. INTRODUCTION TO DOUBLE-BETA DECAY

For many nuclei with even numbers of both protons and neutrons, a rare transition that changes the atomic number by two units is possible. This process emits 2 electrons and is referred to as double-beta decay (ββ). Figure 1 shows an example of such decay for the nucleus ^{76}Ge. Double-beta decay can occur within the standard model as a second order weak process when the electrons are accompanied by the emission of 2 anti-neutrinos. This two-neutrino double-beta decay (ββ(2ν)) process is very rare and was first observed [1] in the laboratory in 1987: a full 50 years after its decay rate was initially estimated [2]. Since that initial detection it has been observed in more than 10 nuclei.

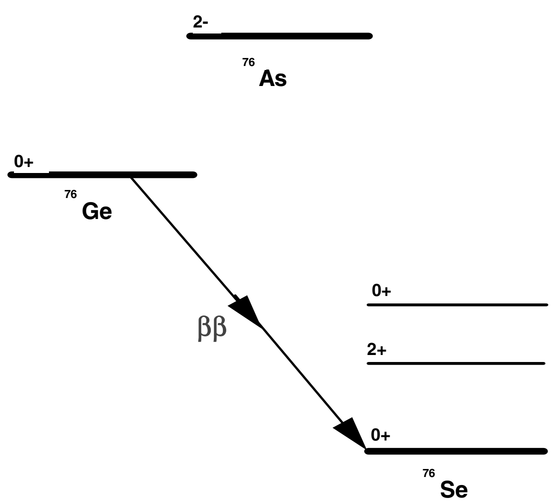

Figure 1: The decay scheme of ^{76}Ge showing the ββ transition to the ground state of ^{82}Se.

The current interest in double-beta decay focuses on the alternative zero-neutrino process (ββ(0ν)). If the neutrino has certain characteristics, this manifestly lepton-number-violating process decay can proceed with no neutrino emission and only the 2 electrons in the final state. In this case, one envisions a virtual exchange of a neutrino between 2 neutrons within the nucleus leading to the decay. (See Fig. 2.) In the standard model, when a neutron decays it emits a right-handed antineutrino, whereas neutrons absorb left-handed neutrinos. Therefore, for this exchange to occur, the neutrino must be its own antiparticle; that is a Majorana particle. In addition, it must have some mass so it won't be in a pure helicity state. The development of the next standard model of particle physics requires that we form an understanding of these two characteristics of the neutrino. Since ββ is the only practical way to address the particle-antiparticle nature of the neutrino, the field of research has taken on special importance.

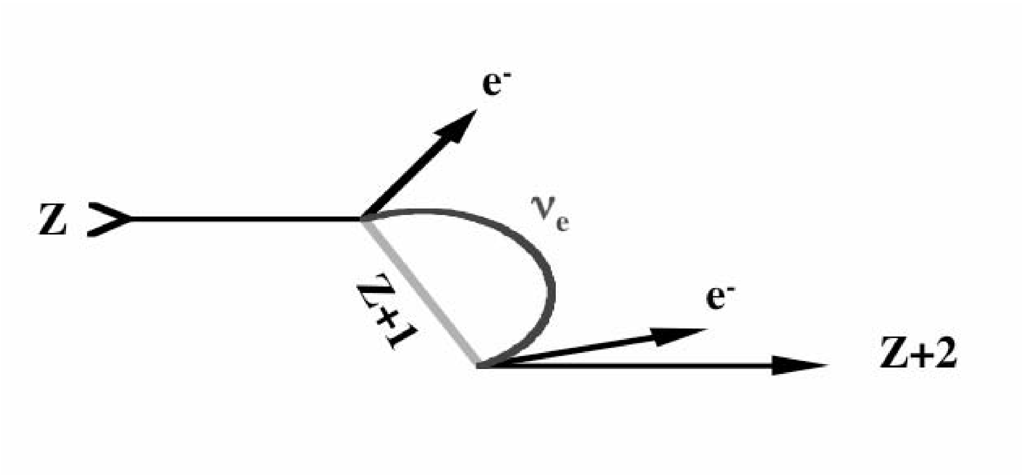

Figure 2: A Feynman "sketch" of ββ(0ν).

The ββ(0ν) decay rate (Γ) can be written as a product of 3 factors; a phase space term ($G_{0\nu}$), a matrix element ($|M_{0\nu}|$) and an effective neutrino mass factor ($m_{\beta\beta}$).

$$\Gamma = G_{0\nu} |M_{0\nu}|^2 m_{\beta\beta}^2$$

The observation of ββ(0ν) will demonstrate that the neutrino is a Majorana particle and the rate of the decay determines the effective neutrino mass. This effective mass is related to the light neutrino mass eigenvalues (m_j) and the mixing parameters (U_{ej}).

$$m_{\beta\beta} = |\Sigma m_j U_{ej}^2|$$

The interest in ββ has blossomed recently because of the observation of neutrino oscillations. These measurements have indicated that neutrinos do have a mass. Although, oscillation experiments do not determine the absolute mass scale, the indications are that the mass might be in range to produce an observable ββ(0ν) rate. Oscillation experiments measure the difference in the squares of mass eigenvalues. Atmospheric neutrino studies have found evidence for neutrino oscillations with a $\delta m^2 \sim (50\ \text{meV})^2$ and the solar neutrino experiments have found evidence for a $\delta m^2 \sim (8\ \text{meV})^2$. As a result of these measurements, at least one neutrino must have a mass greater than ~50 meV. In addition a recent claim for the observation of ββ(0ν) indicates that the neutrino masses are degenerate; that is all the m_j are about equal and greater than about 200 meV.

Recent reviews of the field can be found in References [3], [4], [5], [6].

2. AN IDEAL DOUBLE-BETA DECAY EXPERIMENT

ββ(0ν) experiments only detect the electrons in the final state. The sum of the energies of the two electrons will be a peak at the Q-value for the decay. The decay rate is extremely low, however, and hence the peak will be very small. Technically, the difficulty of these experiments centers on the ability to find a small peak superimposed on the inevitable continuum of background. For an $m_{\beta\beta}$ of 50 meV, one needs to be sensitive to half-lives near 10^{27} y: 10^{17} times longer than the age of the Universe. It is a great challenge to build an experiment large enough with a sufficiently low background to observe such a tremendously long half-life.

The first direct measurement of ββ(2ν) used a time projection chamber [1]. This was a fairly large apparatus (see Fig. 3) for a modest amount of source (13 g) and therefore, it is doubtful that this type of arrangement will represent the best of the next generation of ββ(0ν) experiments. This design doesn't scale easily to a very large source mass with very low backgrounds. It is interesting to try to enumerate the features that an ideal ββ(0ν) experiment would posses. It would have the following characteristics:

- The detector mass must be large enough to detect the very rare decay.
- The ββ(0ν) source must be extremely low in radioactive contamination.
- The proposal must be based on a demonstrated technology for the detection of ββ.
- Although the use of natural isotope will be less costly, the enrichment process provides a good level of purification and also results in a (usually) much smaller volume detector.
- A small detector volume minimizes internal backgrounds, which scale with the detector volume. It also minimizes external backgrounds by minimizing the shield volume for a given stopping power. An apparatus whose source is also the detector most easily accomplishes this. Alternatively, a very large source may have some advantage due to self-shielding.
- Good energy resolution is required to prevent the tail of the ββ(2ν) spectrum extending into the ββ(0ν) region of interest.
- Ease of operation is required because these experiments usually operate in remote locations.
- A large Q value results in a fast ββ(0ν) rate and also places the region of interest above many potential backgrounds.
- A relatively slow ββ(2ν) rate also helps control this background.
- Identifying the daughter in coincidence with the ββ decay energy would eliminate most potential backgrounds except ββ(2ν).
- Event reconstruction, providing kinematic data such as opening angle and individual electron energy, can aid in the elimination of backgrounds. This data might also help elucidate the physics if a statistical sample of ββ(0ν) events is observed.
- Good spatial resolution and timing information can help reject background processes.
- The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

Figure 3: Michael Moe is shown standing by the time projection chamber used for the first direct observation of ββ(2ν) [1].

No experiment, past or proposed, is able to optimize for all of these characteristics simultaneously. Each has chosen a design that emphasizes different aspects of this list.

3. PRESENT EXPERIMENTAL STATUS

Table 1 summarizes the best ββ(0ν) results to date. Note that the half-life limits vary by about 4 orders of magnitude, whereas the mass limit varies by only a factor of about 20. This reflects the fact that the decay rate is proportional to the effective mass squared.

Table 1: Best reported limits on the ββ(0ν) half-life. The mass limits are those quoted by the authors using their choice of matrix elements. All limits are 90% CL, except where noted.

Isotope	**Half-life (years)**	**$m_{\beta\beta}$ (meV)**	**Reference**
^{48}Ca	>1.4 x 10^{22}	<7200-44700	[7]
^{76}Ge	>1.9 x 10^{25}	<350	[8]
^{76}Ge	>1.6 x 10^{25}	<330-1350	[9]
^{76}Ge	=1.2 x 10^{25}	=440	[10]
^{82}Se	>2.7 x 10^{22} (68%)	<5000	[11]
^{100}Mo	>5.5 x 10^{22}	<2100	[12]
^{116}Cd	>1.7 x 10^{23}	<1700	[13]
^{128}Te	>7.7 x 10^{24} (geochem)	<1100-1500	[14]
^{130}Te	>5.5 x 10^{23}	<370-1900	[15]
^{136}Xe	>4.4 x 10^{23}	<1800-5200	[16]
^{150}Nd	>1.2 x 10^{21}	<3000	[17]

The state of the art is clearly the Ge experiments. IGEX [9] and Heidelberg-Moscow (HM) [8] both used ~10 kg of Ge detectors enriched to 86% in isotope 76. The two experiments had very similar backgrounds and similar limits with the HM result being marginally superior. A small number of the HM collaboration reanalyzed the data along with some additional run time and presented evidence for a positive result [10]. This controversial claim is for a half-life of 1.2 x 10^{25} y corresponding to a degenerate neutrino mass spectrum. The result awaits confirmation. (See Ref. [4] for a summary of the literature concerning the controversy.

4. BACKGROUNDS

The search for double-beta decay is mostly an effort to reduce backgrounds in order to improve the sensitivity to every longer half-lives. Here, the backgrounds are classified into 3 categories: natural radioactivities, two-neutrino double-beta decay and cosmogenic radioactivities.

4.1. Natural Radioactivity

Many $\beta\beta$ experiments also serve as dark matter searches. Those searches look for the low-energy recoils resulting from elastic scattering of Weakly Interacting Massive Particles (WIMPS). The potential background for those searches is more varied than for $\beta\beta(0\nu)$. Because the $\beta\beta(0\nu)$ endpoint is typically a few MeV, many natural radioactivities simply contribute too little energy to pollute that region of interest.

The most important naturally occurring isotopes that are potential backgrounds for $\beta\beta(0\nu)$ are ^{208}Tl and ^{214}Bi. These have large Q-values and can pollute the region of interest of almost all $\beta\beta$ isotopes. They are members of the natural Th and U decay chains and thus common in the environment. Furthermore, they are daughters of the gaseous Rn isotopes, which are very mobile. The Th and U half-lives, (~10^{10} y), are much shorter than the required 10^{26} to 10^{27} y sensitivity for $m_{\beta\beta}$ = 50 meV. Therefore even a tiny amount of these activities are a significant problem. Over the past 60 years, experimentalists have made great progress in identifying materials that are very low in Th and U. By building their experiments from this limited palate of materials, these activities have been greatly reduced. Improved purification techniques have also helped eliminate these backgrounds.

Radon is a special problem because it’s a gas that emanates from U and Th containing compounds and diffuses through many materials also. Experimenters must ensure that the detector volume is kept free of Rn. In many cases a careful flushing of the atmosphere near the inner volume with boil-off gas from liquid nitrogen sufficiently reduces the Rn. At liquid nitrogen temperatures, Rn is frozen out and therefore the boil-off gas is mostly free of Rn.

There are techniques to tag Tl and Bi background events based either on the kinematics of the decay processes or on delayed coincidence timing of the progenitors and daughter members of the natural decay chains. Although there has been great success in reducing backgrounds in this way, all these techniques have some inefficiency. Therefore it is necessary to minimize these activities. The future proposals will make great efforts to reduce the amount of Tl and Bi present even if they rely on such tagging techniques.

Many isotopes not normally found in nature (*e.g.* ^{239,240}Pu, ^{137}Cs, ^{90}Sr, ^{42}Ar, and ^{85}Kr are produced artificially by human activities such as nuclear weapon testing, nuclear accidents, reactor venting, *etc*. Therefore it is necessary for experimenters to consider such exotic possibilities when designing an experiment.

4.2. Two-Neutrino Double-Beta Decay

Unlike ββ(0ν), the two electrons share the available energy with two neutrinos in the ββ(2ν) process. Thus their sum energy spectrum is a distribution up to the endpoint. (See Fig. 4.) This spectrum is very steeply falling and, in principle, the region of interest for ββ(0ν) should be free of such events. However, the finite resolution of any detector can result in ββ(2ν) events polluting the ββ(0ν) region.

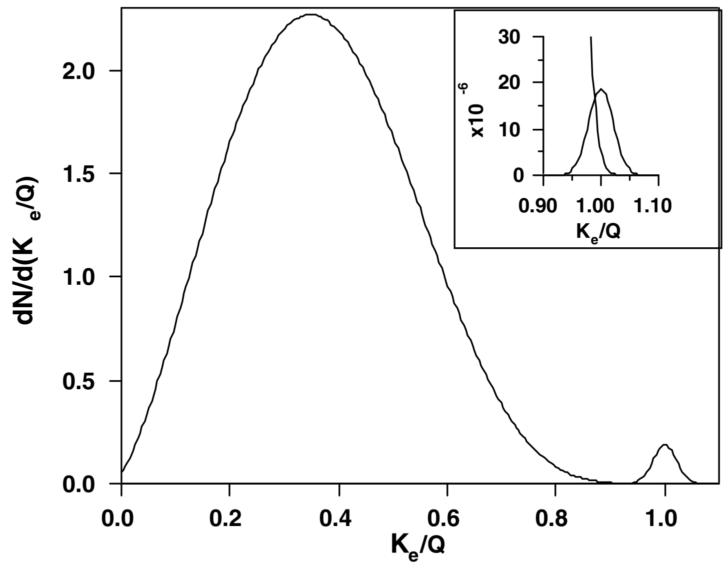

Figure 4: Illustration of the spectra of the sum of the electron kinetic energies K_e (Q is the endpoint) for the ββ(2ν) spectrum normalized to 1 (dotted curve) and ββ(0ν) decays (solid curve). The ββ(0ν) spectrum is normalized to 10^{-2} (10^{-6} in the inset). All spectra are convolved with an energy resolution of 5%. (Figure is taken from Ref. [3].)

4.3. Cosmogenic Radioactivity

Cosmic rays react with a detector and produce signals. Because the cosmic ray flux is so high on the surface of the Earth, ββ experiments are conducted underground. Going to a deep location and incorporating an anti-coincidence shield can eliminate any prompt events. But in addition to prompt interactions, cosmic rays can produce delayed radioactivity via many nuclear reactions. In particular, while detector materials or the source resides on the surface of the Earth, they are exposed to a significant fast (>10 MeV) neutron flux. These fast neutrons can produce large ΔA transitions in nuclei that result in radioactive nuclides.

Below ground the fast neutron flux is proportional to the cosmic-ray muon flux, so going deeper reduces it. For most cases, a few hundred meters will suffice to eliminate the *in situ* production and only the residual activity left over from the time spent on the surface will be present. The most famous example of this effect is that of ^{68}Ge in Ge detectors. Even though the experiments used Ge enriched in ^{76}Ge, ^{68}Ge was produced in the crystals through the high-threshold reaction, ^{76}Ge (n,9n) ^{68}Ge. In using enriched Ge with little ^{70,72,73,74}Ge, experimenters had thought that the ^{68}Ge problem would not be present because the required reaction on ^{76}Ge had such a large ΔA. Although it was significantly decreased, it remained a source of background.

For future experiments that will require sensitivities near 1 event/year in the region of interest in a 1-ton sample, the cosmogenic background possibilities are varied. Because the signal rate is very low in a large target, rare processes must be considered as potential backgrounds.

5. FUTURE EXPERIMENTS

There are many programs either proposed or under development for the study of ββ(0ν) and Table 2 summarizes those projects of which I'm aware. There are far too many to present details on all. Therefore in this section, I have chosen 4 programs as representative of ββ experimental research. These four, Majorana, GERDA, EXO and CUORE are likely to construct apparatus using a few hundred kg of isotope in the coming years in a configuration that could be scaled to a ton-scale experiment.

Table 2: Proposed or suggested future ββ(0ν) experiments.

Experiment	Source	Detector Description	Reference
CAMEO	116Cd	$CdWO_4$ scintillating crystals in liquid scintillator	[18]
CANDLES	48Ca	CaF_2 scintillating crystals in liquid scintillator	[19]
CARVEL	^{48}Ca	$CaWO_4$ scintillating crystals	[20]
COBRA	Various	CdTe semiconductors	[21]
CUORE	^{130}Te	TeO_2 crystals operated as bolometers	[22]
DCBA	^{150}Nd	Nd foils and tracking chambers	[23]
EXO	^{136}Xe	Xe Time Project Chamber (TPC)	[24]
GEM	^{76}Ge	Bare Ge detectors in liquid nitrogen	[25]
GENIUS	^{76}Ge	Bare Ge detectors in liquid nitrogen	[26]
GERDA	^{76}Ge	Bare Ge detectors in liquid nitrogen	[27]
GSO	^{160}Gd	Gd_2SiO_5 scintillating crystals in liquid scintillator	[28], [29]
Majorana	^{76}Ge	Segmented Ge detectors	[30]
MOON	^{100}Mo	Mo foils interleaved with plastic scintillator	[31]
Nano-Crystals	Various	Suspended nanoparticles in scintillator	[32]
Super-NEMO	Various	Metal foils interleaved with tracking chambers	[33]
Xe	^{136}Xe	Xe dissolved in liquid scintillator	[34]
XMASS	^{136}Xe	Liquid Xe	[35]

5.1. Majorana

The Majorana Collaboration proposes to field 120 kg of 86% enriched Ge detectors [30]. (See Fig. 5.) The detector design is very modular and could be easily expanded to reach sensitivity to the mass scale indicated by the atmospheric neutrino oscillation experiments. By using segmented crystals and pulse-shape analysis (PSA), multiple-site events can be identified and removed from the data stream. Internal backgrounds from cosmogenic radioactivities will be greatly reduced by these cuts and external γ-ray backgrounds will also be preferentially eliminated. Remaining will be single-site events like that due to ββ. The sensitivity is anticipated to be 4 x 10^{27} y.

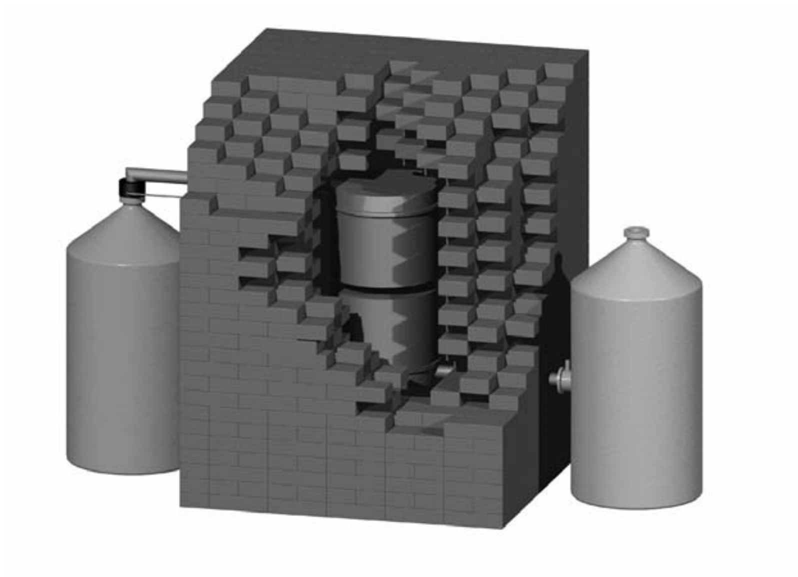

Figure 5: A concept design of the Majorana apparatus. The inner Cu cryostats are shown in the cutaway of the lead shield. Each of the two cryostats holds about 60 kg of Ge detectors.

Several research and development activities are currently proceeding. The collaboration is building a multiple-Ge detector array, referred to as MEGA, that will operate underground at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM USA. This experiment will investigate the cryogenic cooling of many detectors sharing a cryostat in addition to permitting studies of detector-to-detector coincidence techniques for background and signal identification.

A number of segmented crystals are also being studied to understand the impact of segmentation on background and signal. This SEGA program consists of one 12-segment enriched detector and a number of commercially available segmented detectors. Presently, commercially available segmented detectors are fabricated from n-type crystals. Such crystals are much more prone to surface damage and thus more difficult to handle when packaging inside their low-background cryostats. Hence the collaboration is also experimenting with segmenting p-type detectors.

Figure 6 shows a Th spectrum taken with a commercially available segmented Clover™ detector. This detector is a close-pack array of 4 Ge detectors that are each segmented in half axially forming two hemi-cylinders. The spectrum itself is the sum of the 4 individual detector spectra. Pulse shape analysis tends to identify multiple energy deposits that are separated radially. Segmentation tends to identify multiple energy deposits axially, in the case of the Clover™ and axially plus longitudinally in general. Data taken with this detector indicates that these two cuts act on different subsets of the data and therefore the rejection using both cuts in succession is better than predicted from the individual rejections. The spectrum shows the double-escape peak (DEP) from the ^{208}Tl 2.6 MeV line at 1.592 MeV and a nearby ^{228}Ac γ ray at 1.588 MeV. By the nature of their interactions, the DEP is a single-site energy deposit similar to ββ, whereas the γ ray tends to be a multiple site event. After the two cuts, this preliminary data study indicates that 73% (7%) of the DEP (γ-ray) events are retained.

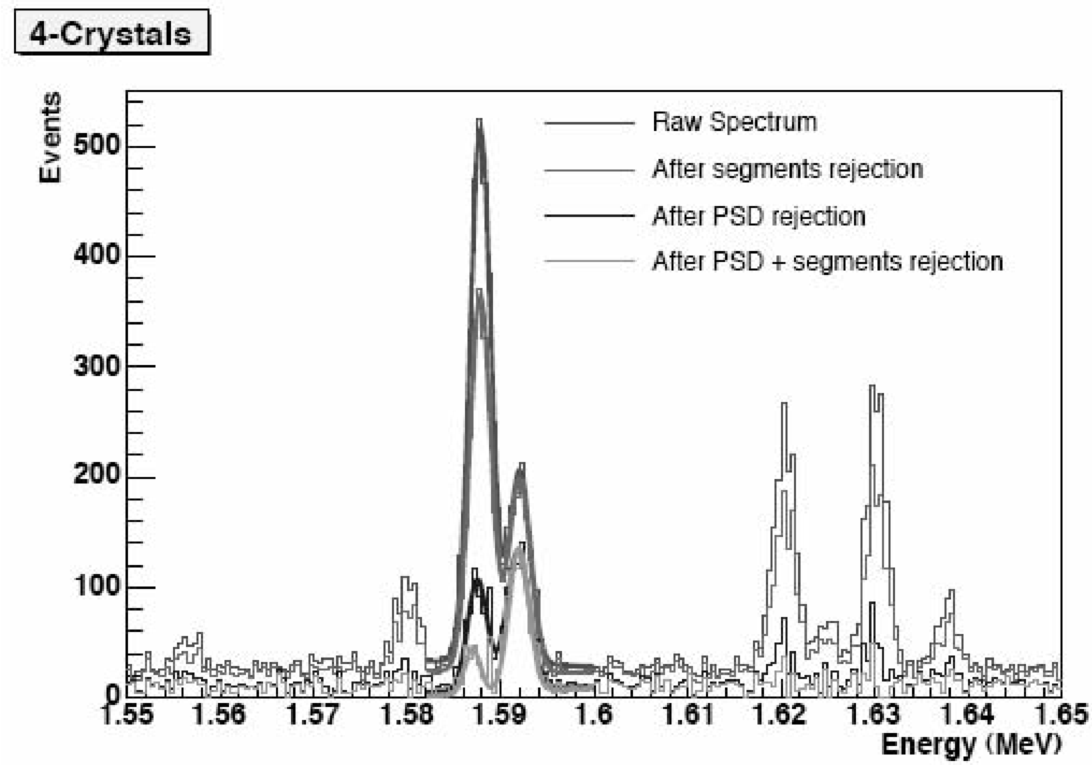

Figure 6: A Th spectrum indicating the results of various cuts on the double-escape peak of the 2.6-MeV ^{208}Tl γ ray and the nearby ^{228}Ac γ ray.

5.2. GERmanium Detector Array (GERDA)

The GENIUS collaboration [26] proposed to install 1 t of enriched bare Ge crystals in liquid nitrogen. By eliminating much of the support material surrounding the crystals in previous experiments, this design is intended to reduce backgrounds of external origin. Note how this differs from the background-reduction philosophy associated with pulse-shape analysis coupled with crystal segmentation. The primary advocates for this project indicate [10] that its motivation has been questioned by their own claim of evidence for ββ(0ν) decay. Even so, the GENIUS test facility [36] is being operated to demonstrate the effectiveness of operating crystals naked in liquid cryogen.

Another group at the Max Plank Institute in Heidelberg, however, is proposing to pursue a similar idea. They have recently submitted a Letter of Intent [27] to the Gran Sasso Laboratory. They propose to collect the enriched Ge crystals from both the Heidelberg-Moscow and IGEX experiments and operate them in either liquid nitrogen or liquid argon. As a second phase of the proposal, they plan to purchase an additional 20 kg of enriched Ge detectors (most likely segmented) and operate with a total of 35 kg for about 3 years. Finally, they eventually plan to propose a large ton-scale experiment. Figure 7 shows the GERDA concept design. It should be noted that this collaboration and the Majorana collaboration are cooperating on technical developments and if a future ton-scale experiment using ^{76}Ge proceeds these two groups will most likely merge and optimally combine the complementary technologies of bare-crystal operation and PSA-segmentation.

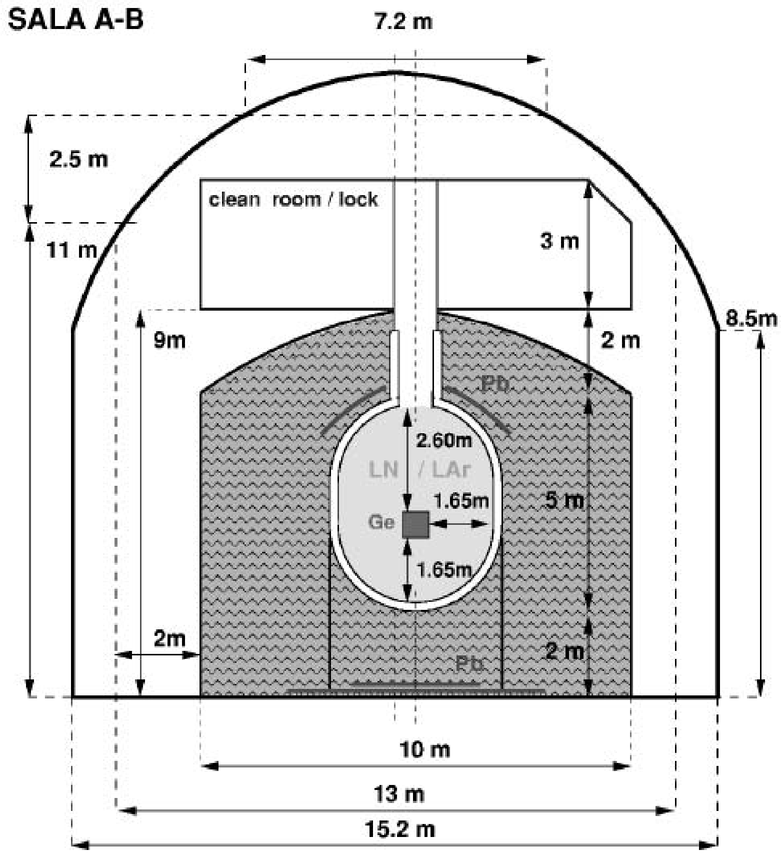

Figure 7: Cross section of the baseline cryogenic and water vessel system with clean room and lock on top. The outer contour line shows the cross section of Hall A at the Gran Sasso Laboratory. Figure courtesy of the GERDA collaboration.

5.3. Enriched Xenon Observatory (EXO)

The EXO project proposes to use 1-10 t of about 80% enriched liquid Xe as a time projection chamber [Dan00]. Development of a high-pressure gas TPC is being pursued in parallel. In addition to measuring the energy deposit of the electrons, the collaboration is developing a technique for extracting the daughter Ba ion from the Xe and detecting it offline. Observing the daughter in real time with the ββ decay is a powerful technique for reducing background. With a 1-ton experiment, they anticipate sensitivity to a lifetime of 8 x 10^{26} y.

The collaboration has had some good progress on the research and development required to demonstrate that this technically challenging project is feasible. They have determined the energy resolution by using both ionization and scintillation measurements in liquid Xe. The resolution result σ = 3% stated in [37] was measured at 570 keV. Assuming a statistical dependence on energy this means about 1.5% resolution at the $\beta\beta(0\nu)$ energy of 2480 keV. They have also built an atom trapping system and have observed lone Ba ions in an optical trap. Furthermore, they have begun experiments to demonstrate that the ions are trapped and observable in an appreciable Xe gas background [38]. Finally, using a ^{222}Ra source they are testing the Ba extraction technology. Ra and Ba have similar chemistry, but the radioactive decay of Ra makes it a convenient test material.

The EXO team is currently preparing a 200-kg enriched-Xe experiment to operate at the Waste Isolation Pilot Plant (WIPP). This prototype will not initially include Ba extraction.

5.4. Cryogenic Underground Observatory for Rare Events (CUORE)

The CUORICINO experiment uses 41 kg of TeO_2 crystals operated at 10 mK as bolometers. During the initial cool down, some of the cabling failed and hence not all crystals were active. As a result the initial run had contained about 10 kg of ^{130}Te [22]. An initial exposure of 5.46 kg-y, with an energy resolution of 9.2 keV FWHM resulted in a half-life limit > 7.2 x 10^{23} y at 90% confidence level [39]. The background in the region of interest for this run was 0.22 ± 0.04 counts/(keV kg y). Afterward, a 3-year run with the full mass will have a sensitivity of 10^{25} years.

The CUORICINO project is a prototype for the CUORE proposal. CUORE would contain 760 kg of TeO_2. With the anticipated improvement in background to better than 0.01 counts/(keV kg y), the half-life sensitivity is ~7 x 10^{26} y or a few 10's of meV for $m_{\beta\beta}$ [22].

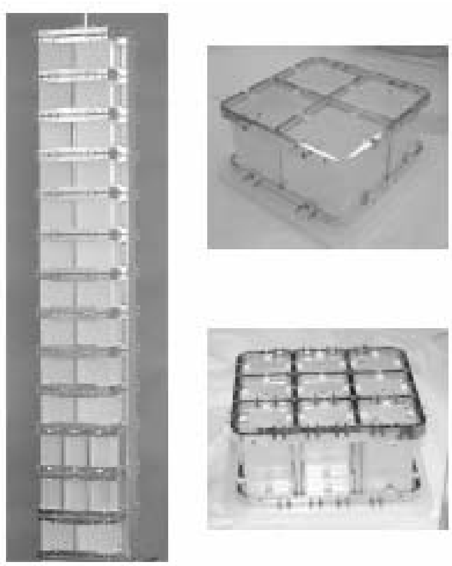

Figure 7: Photographs of the CUORICINO tower, one 4-crystal module and the single 9-crystal module. Photo courtesy of the CUORE collaboration.

6. CONCLUSIONS

Because the recent neutrino oscillation experiments indicate that neutrinos do have mass, double-beta decay has seen a great resurgence in interest. There are a large number of programs around the world attempting to build experiments large enough to measure double-beta decay at the degenerate mass scale with hopes of scaling to the atmospheric scale. At these sensitivities, one has great hope of a discovery and even null results will constrain neutrino mass models significantly.

Acknowledgments

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