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Current status of neutrinoless double-beta decay searches

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ABSTRACT

This article briefly reviews the current status and near-term prospects of experimental searches for neutrinoless double-beta decay. After discussing the motivation and history of neutrinoless double-beta decay, we will focus on the status of current experiments and the factors limiting their sensitivity. We will then discuss the prospects and requirements for proposed experiments that will probe the inverted neutrino mass hierarchy.

1. Introduction and motivation

Neutrinos are fundamental particles within the Standard Model of particle physics. They are the only fermions that do not carry electrical charge and they also have no color charge. The only quantum number that can be used to distinguish between neutrino (ν) and anti-neutrino ($\bar{\nu}$) states is lepton number. However, there is no gauge symmetry associated with lepton number and there is no fundamental reason this quantity should be conserved. There are many extensions to the Standard Model that do not require lepton number conservation. If lepton number is violated, the distinction between ν and $\bar{\nu}$ is unclear and it becomes possible that neutrinos can be their own anti-particles or so-called Majorana fermions [1]. In contrast, all other Standard Model fermions have distinct anti-particle states and are known as Dirac fermions.

Interestingly, experimental results to date are consistent with both Majorana and Dirac neutrinos. Determining the nature of neutrinos is difficult because of the small neutrino masses and the handedness of the weak interaction, but a promising approach is to search for the neutrinoless double-beta decay ($\beta\beta(0\nu)$-decay) of an atomic nucleus, given as [2,3]:

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \tag{1}$$

It is obvious that this is also a lepton number violating ($\Delta L = 2$) process. Though many different processes could potentially mediate this decay, such as the exchanges of massive Majorana neutrinos or supersymmetric particles (see [4,5] for a review), just the observation of this decay is sufficient to show that the neutrino is a Majorana fermion [6].

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Collider experiments, such as the LHC, are able to probe lepton number violating processes that could contribute to $\beta\beta(0\nu)$-decay [5,7–16], but direct searches for the decay are the only way to probe the Majorana vs. Dirac nature of the neutrino in a model-independent manner. Any limits or direct measurements of the half-life of $\beta\beta(0\nu)$-decay can also be used to constrain the absolute neutrino mass scale, assuming that the $\beta\beta(0\nu)$-decay process is dominated by the exchange of massive Majorana neutrinos. The next generation of experiments will attempt to have sensitivity down to $10-20\,\text{meV}$ for the effective majorana neutrino mass, which would cover the so-called inverse neutrino mass hierarchy regime. However, unravelling the contributions from other new physics could make the implications of a definitive half-life measurement

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Table 1
Some $\beta\beta(0\nu)$-decay isotopes of experimental interest that are discussed in this paper, shown with most recent half-life limits. Natural abundances and Q-values taken from [28].

Isotope	$\beta\beta(0\nu)$ Half-life limit (years)	Natural Abundance [%]	Q-value (MeV)
^{48}Ca	$>1.4\times10^{22}$ [31]	0.187	4.2737
^{76}Ge	$>3.0\times10^{25}$ [32]	7.8	2.0391
^{82}Se	$>1.0\times10^{23}$ [33]	9.2	2.9551
^{100}Mo	$>1.1\times10^{24}$ [34]	9.6	3.0350
^{130}Te	$>4.0\times10^{24}$ [35]	34.5	2.5303
^{136}Xe	$>1.1\times10^{25}$ [36]	8.9	2.4578
^{150}Nd	$>1.8\times10^{22}$ [37]	5.6	3.3673

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for neutrino mass difficult to quantify [4,5,17]. In addition, the nuclear physics involved in the decay requires the difficult calculation of nuclear matrix elements (NMEs) to relate the observed decay rate to neutrino mass (see [18–20] for recent reviews). Despite this, $\beta\beta(0\nu)$-decay mass constraints are still complementary to those from direct neutrino mass experiments, such as Tritium-endpoint measurements like KATRIN [21] and Project 8 [22], electron-capture experiment like ECHo [23], and cosmology [24]. See [25,26] for recent reviews of direct mass measurement experiments.

This paper provides a very brief review of the current status of experimental searches for $\beta\beta(0\nu)$-decay and the challenges that they face as they scale to the next generation. The literature related to $\beta\beta(0\nu)$-decay is extensive and for more detailed recent reviews of the phenomenology and experimental aspects of $\beta\beta(0\nu)$-decay, the reader is referred to [16,18,27–29].

2. The experimental approach and challenges

Though $\beta\beta(0\nu)$-decay is energetically allowed for many isotopes, only 35 of these are stable against or have highly suppressed single beta decays and are of experimental use [30]. Further considerations, described below, apply additional constraints to which isotopes are suitable. Shown in Table 1 are a list of isotopes of particular experimental interest that will be discussed in this paper. Note that the half-life limits are extremely long ($\sim10^{24}$ yr.) and sets the scale for the next generation of experiments.

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2.1. Signal detection

$\beta\beta(0\nu)$-decay is characterized by the nuclear emission of two electrons and no anti-neutrinos. The recoil energy of the nucleus is negligible and most of the energy is carried away by the electrons. The most direct experimental approach is to measure the sum energy of the electrons, since $\beta\beta(0\nu)$-decay will manifest as a characteristic peak in the sum energy spectrum at the Q-value of the decay. Other information can also be collected. Tracking detectors can reconstruct the topology of the event and distinguish events with two electrons emitted, such as $\beta\beta(0\nu)$-decay, from events that yield a single electron. The latter includes normal beta decay or a Compton recoil from a scattered gamma-ray. Atomic techniques can be applied to identify the daughter isotope as additional confirmation of a $\beta\beta(0\nu)$-decay event, as discussed below.

2.2. Radioactive backgrounds

The most significant experimental challenge for $\beta\beta(0\nu)$-decay experiments is the reduction of ionizing radiation backgrounds. Certain naturally occurring radio-isotopes can create background events in $\beta\beta(0\nu)$-decay searches that mimic $\beta\beta(0\nu)$-decay signals. Long-lived primordial isotopes like ^{232}Th and ^{238}U are ubiquitous in the earth's crust and all construction and target materials. The high-energy gamma-rays that some of their daughters emit during decays can undergo ionizing interactions in the detector materials that mimic $\beta\beta(0\nu)$-decay signals or interfere with analysis cuts. For example, ^{208}Tl in the ^{232}Th decay chain emits an intense line at 2.614 MeV that is above the Q-value of several $\beta\beta(0\nu)$-decay isotopes of interest, and ^{214}Bi from the ^{238}U decay chain emits gamma-rays at many different energies out to 3184 keV. $\beta\beta(0\nu)$-decay experiments resort to extreme measures to improve the radiopurity of construction and target materials in order to remove these radioactive isotopes, though which backgrounds dominate and what measures are required are experiment-specific. $\beta\beta(0\nu)$-decay experiments also require shielding against environmental gamma-rays via high-density materials (ie. lead), cryogenic liquids, water, or combinations thereof. Some shielding designs are instrumented to provide additional background veto power. Experiments that use lead as shielding may even use archaeological lead that is low in radioactive ^{210}Pb, which has a half-life of 22.2 years [38].

^{222}Rn is part of ^{238}U decay chain, has a half-life of 3.82 days, and is an especially pernicious background. It seeps from rocks, concrete, and detector construction materials and is a chemically inert noble gas. When it decays, the daughter ion is electrostatically attracted to nearby surfaces, making plate-out a significant concern, especially in bolometric and other

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detectors that have sensitive surfaces. In addition, ^{214}Bi is a daughter isotope of ^{222}Rn, which provides a background of gamma-rays. All $\beta\beta(0\nu)$-decay experiments require some form of Rn mitigation.

All isotopes that can undergo $\beta\beta(0\nu)$-decay can also undergo a related decay called two neutrino double-beta decay ($\beta\beta(2\nu)$-decay), given as:

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e \quad (2)$$

This is an allowed second-order weak process that has been observed in isotopes of experimental interest with half-lives on the order of 10^{20} years [27]. From kinematic arguments it follows that the electrons emitted in this decay have a broad continuum up to the Q-value of the decay. The only way to discriminate these $\beta\beta(2\nu)$-decay from $\beta\beta(0\nu)$-decay is via energy, making experimental energy resolution particularly important.

Finally, all modern $\beta\beta(0\nu)$ experiments require underground locations to reduce cosmic-ray induced backgrounds. Muons produced (via cosmic-ray interactions in the upper atmosphere) are extremely penetrating and can interact directly with the target volume or produce secondary particles via hadronic or electromagnetic interactions in surrounding materials. They can also cause delayed events by activating detector materials and producing so-called cosmogenic radioactive isotopes, such as ^{60}Co in copper, a common construction material in $\beta\beta(0\nu)$-decay experiments. Current experiments require depths on the order of 1 km or greater to mitigate prompt cosmic-ray backgrounds.

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3. Major experimental efforts

In this section we will discuss the major experimental efforts that are currently underway, focussing on experiments that have a demonstrated a path to deploying approximately a tonne of $\beta\beta(0\nu)$-decaying isotope or more. We will also briefly discuss other efforts.

3.1. ^{130}Te program

^{130}Te has the highest natural abundance of any $\beta\beta(0\nu)$ isotope (34.5%), making it an attractive candidate. It has a good Q-value of 2527.518 ± 0.013 keV, though it is close to the sum energy (2505.7 keV) of the gammas emitted in the decay of cosmogenic ^{60}Co from copper. There are currently two major efforts underway to search for $\beta\beta(0\nu)$-decay in this isotope.

3.1.1. CUORE

The Cryogenic Underground Observatory for Rare Events (CUORE) [38] is in the final stages of construction at a depth of 3400 m.w.e. (meters water equivalent) in the Laboratori Nazionali del Gran Sasso (LNGS) near L'Aquila, Italy. It uses cryogenic bolometers [39,40] made from natural (unenriched) tellurium oxide. Each bolometer is a crystal of $5 \times 5 \times 5\,\text{cm}^3$ operated at 10 mK. At this temperature the heat capacity of the crystals is extremely small and microscopic energy deposits, such as those from $\beta\beta(0\nu)$-decays, can yield measurable temperature changes. The temperature of each crystal is measured with a neutron-transmutation-doped Ge thermistor. In CUORE the crystals will be arranged in 19 towers of 52 crystals each, providing a ^{130}Te mass of 200 kg. The tower supports will be constructed from low-background copper and polytetrafluoroethylene (PTFE). CUORE will be shielded by a low-activity lead shield that includes archaeological Roman lead, as well as neutron moderators and radon exclusion system. The electrolytic copper used in the cryostat will provide additional shielding.

CUORE is the current stage of a series of experiments of increasing mass and sensitivity that use the bolometric technique. Most recently, the CUORE collaboration deployed a single string and performed a search for $\beta\beta(0\nu)$-decay. This experiment was called CUORE-0 and was able to achieve a $\beta\beta(0\nu)$-decay limit of $T_{\frac{1}{2}} > 4.0 \times 10^{24}$ y in ^{130}Te [35] from 9.8 kg.y of exposure. CUORE hopes to achieve a 10-year sensitivity of 3.5×10^{26} years with background level of 1 count/t/keV/y [38]. The CUORE approach has very good energy resolution and scalability. Its main drawbacks are background contamination, especially on or near crystal surfaces, complicated cryogenics, and signal readout.

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3.2. SNO+

The SNO+ detector is an upgrade of the Sudbury Neutrino Observatory (SNO) detector [41]. SNO consisted of a 12 m diameter transparent acrylic vessel that was filled with 1 kiloton of ultra pure heavy water (D_2O) [42]. The acrylic vessel was submerged in normal (light) water and observed by approximately 9,500 phototubes. SNO was located in the SNOLAB laboratory at a depth of 6000 m.w.e. in the Creighton mine near Sudbury, ON in Canada. SNO+ is using a substantial portion of the existing SNO infrastructure to field a new neutrino experiment with a primary physics goal being searching for the $\beta\beta(0\nu)$-decay of ^{130}Te. It will also have a physics program based on observing neutrinos from terrestrial and astrophysical sources. SNO+ will use an organic liquid scintillator, Linear Alkyl Benzene (LAB) with a PPO fluor (2,5-diphenyloxazole), loaded with ^{130}Te as detection medium, replacing the heavy water medium from SNO. In addition, SNO+ will also utilize new purification systems, improved PMTs, an improved data acquisition, and a new mechanical support system to accommodate the change in buoyancy between LAB and light water [43].

SNO+ will be able to field a very large mass of isotope but suffers from poor energy resolution compared to other $\beta\beta(0\nu)$ experiments. This makes determining the background and energy calibration extremely important, since the experiment will rely on a statistical subtraction of the residual backgrounds. The SNO+ background will be dominated by $\beta\beta(2\nu)$ events and ^{8}B solar neutrinos that scatter elastically off electrons [43]. Other backgrounds from U/Th contamination and the rock wall are mitigated with material selection, purification, and fiducialization. If this technique works, it may be even possible to scale it to probe the normal neutrino hierarchy [44].

SNO+ is proposing two stages. In the first stage it will be loaded with at least 0.3% (2340 kg) of natural tellurium, equivalent to 800 kg of ^{130}Te. During this phase, which is anticipated to start in 2017, the goal sensitivity is $T_{\frac{1}{2}} > 9.4 \times 10^{25}$ y (90% CL) or a 3σ detection limit at $T_{\frac{1}{2}} > 6.9 \times 10^{25}$ y. Once the detector concept and purification has been demonstrated, the next phase will increase the isotope loading to 3% (8 tonnes of ^{130}Te) and replace the PMTs with high quantum efficiency R5912-HQEs. For this phase the sensitivity goal would be $T_{\frac{1}{2}} > 7 \times 10^{26}$ y (90% CL) or a 3σ detection limit at $T_{\frac{1}{2}} > 4 \times 10^{26}$ y [45].

3.3. ^{136}Xe program

^{136}Xe is a unique isotope because Xenon is a scintillating, noble gas, which allows for different experimental approaches from other isotopes. There are three major efforts at different levels of development to search for the $\beta\beta(0\nu)$-decay of ^{136}Xe.

3.3.1. KamLAND-Zen

KamLAND-Zen [46] is also an upgrade of a previous neutrino experiment, in this case KamLAND, which measured reactor neutrino fluxes. KamLAND-Zen is located inside the Kamioka mine near Toyama city, Japan. In KamLAND-Zen, ^{enr}Xe is dissolved in the liquid scintillator contained in a 1.5 m balloon inside the original KamLAND detector. The volume outside the balloon is also filled with scintillator, providing a powerful active shield against external backgrounds.

For its first phase, KamLAND-Zen deployed 179 kg of Xe enriched to 91.7% in ^{136}Xe. It started in 2011 and collected 85 kg.yr of exposure. Unfortunately the experimental sensitivity was hampered by unexpected ^{110m}Ag contamination of the balloon that yielded a peak very near the $\beta\beta(0\nu)$-decay endpoint. The ^{110m}Ag likely originated from the Fukushima Daiichi nuclear disaster. Despite this contamination the KamLAND-Zen collaboration was able to set a limit of $T_{\frac{1}{2}} > 1.9 \times 10^{25}$y (90% CL) [46]. The collaboration replaced the balloon and also loaded additional isotope for a total mass of 383 kg for the second phase. They collected only an additional 27.6 kg.years of exposure, but reduced the ^{110m}Ag background by a factor of 10. By combining the two phases, KamLAND-Zen was able to achieve $T_{\frac{1}{2}} > 2.6 \times 10^{25}$ y (90% CL) [47].

In the near future KamLAND-Zen plans to rebuild the mini-balloon using cleaner material and to increase the Xe amount to 600 kg. With this, they hope to achieve a half-life sensitivity of 2×10^{26}y. Beyond that the collaboration proposes a major detector upgrade called “KamLAND2-Zen”, of which the main focus is to improve the energy resolution by introducing light-collecting mirrors, new and brighter scintillator, and high quantum efficiency PMTs. They predict it will improve the energy resolution from 4.0% to $<$ 2.5% at the Q-value of the ^{136}Xe decay. They also intend to increase the Xe mass to 1,000 kg or more. With these improvements, they hope to cover the inverted neutrino mass hierarchy down to 20 meV [48]. Though KamLAND-Zen has a smaller isotopic mass than SNO+, this is offset by its better energy resolution.

3.3.2. EXO/nEXO

The Enriched Xenon Observatory (EXO) uses ultra pure liquid xenon (LXe) that is enriched in ^{136}Xe as detection medium and source [49]. It collects the ionization electrons using a time projection chamber (TPC) to achieve three-dimensional event reconstruction. This provides powerful discrimination against Compton-scattered gamma-ray backgrounds that typically deposit energy in multiple locations in the LXe. In addition, EXO measures the scintillation light, which provides an additional measurement of the energy deposit. A monolithic, homogeneous detector like EXO has the benefit of self-shielding that scales linearly with detector dimension, but at the expense of more enriched material, which scales at the detector dimensions cubed.

The first phase, EXO-200, deployed 150 kg of enriched Xenon in 2011 underground at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. It performed searches for $\beta\beta(0\nu)$-decay [36,50] and in 2014 reported a limit of $T_{\frac{1}{2}} > 1.1 \times 10^{25}$ yr at 90% confidence limit. EXO-200 performed extensive and careful materials selection, screening and characterization to achieve the lowest background possible [51,52]. In terms of region-of-interest (ROI) performance, EXO-200 achieved an energy resolution of 4% FWHM at $Q_{\beta\beta}$ FWHM and a background rate of 1.5×10^{-3} counts/keV/kg/yr, which translates to a rate in their ROI of 0.23 counts/kg/yr.

The next proposed phase for EXO is called nEXO [53,54]. The collaboration proposes to field 5 tonnes of ^{enr}Xe in a larger cryostat with a goal sensitivity of $T_{\frac{1}{2}} > 6.6 \times 10^{27}$ y (90% CL) after 5 years of running, with a Majorana neutrino mass sensitivity of $7-18$ meV. As with EXO, nEXO will be a LXe-based imaging TPC. Major experimental improvements include improved self-shielding with the larger mass, increased segmentation for improved event reconstruction, using lower noise Silicon photomultipliers instead of APD to improve energy resolution, and a deeper location, such as SNOLAB. Another possible future upgrade would be to directly tag or retrieve the daughter Ba ion [55].

3.3.3. NEXT

A more recent proposal for searching for $\beta\beta(0\nu)$-decay in ^{136}Xe, called NEXT (Neutrino Experiment with a Xenon TPC), uses enriched gaseous xenon in a high-pressure (15 bar) TPC [56,57]. The lower density of the gas yields longer tracks for electrons from $\beta\beta(0\nu)$-decay that can be reconstructed with a TPC. The increase in ionization energy-loss at the end of the electron tracks produce a characteristic "spaghetti and meatball" structure that can be used to determine the direction that the electron was traveling. It can also clearly discriminate events that have one or two electrons originating from the same vertex, providing a powerful tool to remove backgrounds from external gamma-rays. In addition, this design has better demonstrated ROI energy resolution of 0.5%–0.7% in prototypes than the other Xe approaches. Since it is a monolithic and homogeneous detector, it has the same benefits of scaling; however it will require a large, low background pressure vessel and massive amounts of shielding against external backgrounds that will pose engineering challenges. Possible upgrade paths using magnetic fields and Barium-tagging are also under consideration by the collaboration [58].

3.4. ^{76}Ge program

Germanium is a semiconductor and can be converted into semiconducting radiation detectors that measure ionization charges directly. To achieve the required semiconducting properties of the ∼1 kg High-Purity Germanium (HPGe) detectors required for gamma-ray spectroscopy, processes have been developed to purify germanium to contamination levels of less than one part in 10^{12} [59]. These processes also remove residual radioactive contamination from the stock material, though experiments still have to contend with cosmic-ray induced isotopes. HPGe detectors have the best energy resolution of any $\beta\beta(0\nu)$ technology (0.15% at $Q_{\beta\beta}$) that provides powerful background reduction due to the smaller ROI. The high-resolution also allows superior identification of residual radioactive contamination via precision gamma-ray spectroscopy. The main drawbacks of germanium are the cost of detector fabrication and complexity associated with deploying many detectors in a cryogenic, low radioactivity environment. ^{76}Ge also has a slightly lower $Q_{\beta\beta}$ of 2039 keV than other isotopes of experimental interest, which requires that more potential sources of background have to be considered.

3.4.1. GERDA and the Majorana Demonstrator

The GERmanium Detector Array (GERDA) [60] experiment utilizes a new approach of submerging an array of 86% enriched HPGe detectors directly in the cryogen, in this case liquid argon (LAr). The LAr provides cryogenic cooling and shielding against external gamma-rays. The cryostat that contains the LAr and the HPGe detectors is submerged in a large water tank that serves as an additional active shield. GERDA is deploying their germanium detectors in a phased approach and recently completed its first phase at LNGS [32,61]. During this phase they deployed reprocessed enriched detectors from the previous International GErmanium EXperiment (IGEX) [62,63] and Heidelberg-Moscow (HDM) experiment [64], as well as new detectors from their second phase. GERDA started data-taking in 2011, collected 21.6 kg.yr of exposure, and successfully demonstrated the operation of an array of HPGe detectors submerged in LAr. They also set the best current limit of $\beta\beta(0\nu)$-decay in ^{76}Ge of $T_{\frac{1}{2}} > 2.1 \times 10^{25}$ y, which they combined with previous experiments to yield $T_{\frac{1}{2}} > 3.0 \times 10^{25}$ y. In addition to careful materials selection, GERDA relied on digital pulse-shape analysis of HPGe signals to distinguish between multi-site events, such as Compton scatters, and single-site events that could indicate $\beta\beta(0\nu)$-decay. GERDA is currently deploying their second phase of detectors which will add an additional 20 kg and hope to increase their half-life sensitivity beyond 10^{26} years [65].

The Majorana Demonstrator also uses enriched HPGe detectors that are deployed inside a more conventional low-background passive lead and copper shield with an active muon veto [66]. It is currently being deployed and undergoing commissioning at the Sanford Underground Research Facility in Lead, SD, USA. Copper is used extensively in the Majorana Demonstrator as both construction and inner shielding material. Copper parts located closest to the detectors is made from copper that is electroformed and machined underground at SURF to prevent cosmic-ray production of ^{60}Co. The collaboration intends to deploy 29 kg of enriched detectors and 15 kg of unenriched with a goal of demonstrating a background of 3 counts/ROI/t/y after analysis cuts. Because the Majorana Demonstrator does not have the low-energy ^{39}Ar backgrounds from LAr like GERDA, it is also capable of searching for low-energy rare events [67], such a light-WIMP dark matter [68–72] and solar and cosmological axions [70,73–87].

The Majorana Demonstrator and GERDA collaborations intend to merge and pursue a joint tonne-scale $\beta\beta(0\nu)$-decay experiment that combines the best technology from both collaborations.

3.5. Other isotopes and approaches

^{48}Ca has the highest Q value of $\beta\beta(0\nu)$-decaying isotopes, which makes it experimentally very attractive as a candidate isotope [31]. However, it's natural abundance is very low (0.187%), hence the success of any future experiment will depend on new enrichment techniques. The CANDLES experiment is using scintillating CaF_2 crystals submerged in liquid scintillator and has deployed only 0.3 kg of ^{48}Ca, which limits its sensitivity.

Additional efforts with different isotopes are underway that use thin foils in a gaseous tracking detector (NEMO-3 [88] and SuperNEMO [89]), scintillating bolometers (CUPID [90], LUCIFER [91], AMoRE [92]) and solid TPCs (COBRA) [93,94]. The reader is referred to other review articles that cover these techniques in more detail [16,28,29,95].

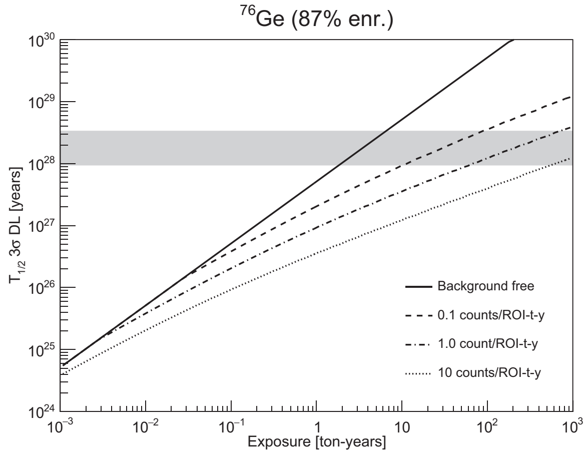

Fig. 1. Shown are the 3σ discovery limits of a germanium experiment as a function of exposure and background limits achieved. The horizontal band shows the inverted neutrino mass hierarchy region, including the uncertainties associated with NMEs and neutrino mixing parameters. It is clear that to completely probe in the inverted neutrino mass hierarchy, the experiment must have extremely low backgrounds of 0.1 cts/t/y, even with 10 t.y of exposure. Other isotopes have similar background requirements.

4. Main considerations for the next generation experiments

The major $\beta\beta(0\nu)$-decay experiments are moving towards building tonne-scale experiments to improve sensitivity. These experiments will be expensive and not all approaches will be able to move forward. Selecting the best technology and isotope(s) will be a formidable challenge that needs to consider NME calculations, *Q*-values of isotopes, backgrounds in the ROI, energy resolution, enrichment, and cost. Several authors have studied this issue, ie. [20,27,95], and this complicated topic is beyond the scope of this brief review. However, an important and sometimes overlooked fact is that the background requirement is just as important as the increased mass, as they occur in a reciprocal relationship in sensitivity estimates. This is shown in Fig. 1. Any increase in isotopic mass must be accompanied by a commensurate reduction in backgrounds.

5. Conclusions

This paper briefly reviewed the current status and future plans of experimental searches for $\beta\beta(0\nu)$-decay. We showed that this is a broad field with a rich array of experimental techniques that is poised to move the next generation of tonne-scale experiments. We argue that reducing detector backgrounds is just as important as mass for the reach of a future experiments and commensurate efforts should be placed to improve both.

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