Reviews in Physics 1 (2016) 29–35

Contents lists available at ScienceDirect

Reviews in Physics

journal homepage: www.elsevier.com/locate/revip

Current status of neutrinoless double-beta decay searches

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ARTICLE INFO

Article history:
Available online 12 March 2016

Keywords:
Neutrinoless double-beta decay

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].

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 $10 - 20\,\mathrm{meV}$ 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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http://dx.doi.org/10.1016/j.revip.2016.03.001

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

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.

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