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Review of neutrinoless double beta decay experiments: Present status and near future

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Abstract

The advancements in neutrinoless double beta decay search are presented. The status and requirements to the technologies of the new generation of experiments are reviewed. The obtained results from the first operational detectors are described.

Keywords: Neutrinoless double beta decay, $T^{0\nu}_{1/2}$, Majorana, neutrino mass, isotopic enrichment

1. Introduction

In the case of 35 radioactive even-even nuclei the nuclear decay into stable isotopes via a single beta emission is energetically forbidden. This can be bypassed with a double beta decay, in which a (A,Z) nucleus directly transforms into (A,Z+2) under the simultaneous emission of 2 electrons ($\beta\beta$) and 2 antineutrinos (2ν) [1]. So far, this so-called $2\nu\beta\beta$ decay has been observed in 11 isotopes and the measured half-lives were found to be in the range of 10^{19} to 10^{24} yr [2]. Another but fundamentally different alternative has been proposed for a long time [3], in which the $\beta\beta$ decay occurs without the emission of antineutrinos (0ν). The experimental signature would be a full-energy peak at the $Q_{\beta\beta}$ value of the $\beta\beta$s rather than a β-like continuum as in the case of the $2\nu\beta\beta$ spectrum. The existence of the $0\nu\beta\beta$ decay would require that neutrinos are massive and their own antiparticles; I.e. have Majorana character [4]. This would lead unambiguously to lepton number violation which is a clear rupture with the current Standard Model of elementary particle physics. Neutrino oscillation experiments have already demonstrated the massive character of neutrinos. However, these have access only to the squared mass difference of neutrino mass eigenstates m_j and the mixing angles U_{ej}. On the contrary, the observation of the $0\nu\beta\beta$ decay would allow the measurement of the effective neutrino mass $\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U_{ej}^2\right|$ and thus define the still unknown absolute neutrino mass scale. Herein, the half-life of the $0\nu\beta\beta$ decay is correlated with $\langle m_{\beta\beta}\rangle$ via:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Z, Q_{\beta\beta}) \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \qquad (1)$$

with $G^{0\nu}$ being the phase space factor and $M^{0\nu}$ the nuclear matrix element. The latter parameter is deduced from a hardly calculable nuclear physics problem and is therefore source of a large systematic uncertainty.
Figure 1 shows the allowed regions of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass eigenstate. These are constrained by the neutrino oscillation parameters and cosmological observations. A so-called degenerate, inverted or normal mass hierarchy might hold with $\langle m_{\beta\beta}\rangle$ in the range of (0.1-0.5) eV, (0.02-0.05) eV and <0.003 eV, respectively. Among the first generation of $0\nu\beta\beta$ decay projects, the Heidelberg-Moskow (HdM) experiment set the most stringent limit with $\langle m_{\beta\beta}\rangle$ <0.35 eV (90% C.L.) in 2001 [5], followed by a controversial claim of observation by a subgroup of the same experiment with $\langle m_{\beta\beta}\rangle \approx$ (0.24-0.58) eV [6].

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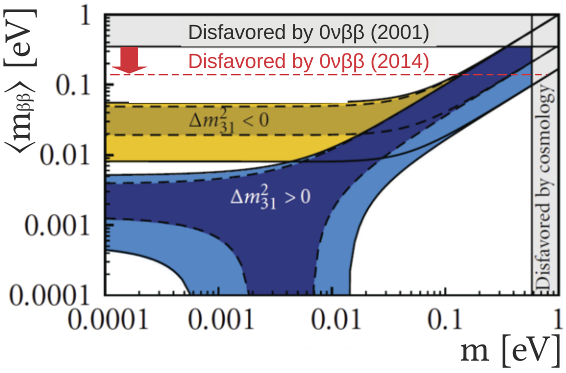

Figure 1: Effective neutrino mass against smallest neutrino mass eigenstate. Modified plot from [7].

2. New generation of $0\nu\beta\beta$ decay experiments

Table 1 summarizes the $0\nu\beta\beta$ decay experiments which are currently operational or under construction, and several on-going R&D projects. The selected $\beta\beta$ isotopes with some properties are added. The large number of experimental approaches reflects the non-existence of one single outstanding $\beta\beta$ candidate isotope and technology that fulfil all requirements needed for reaching a high sensitivity.
In terms of isotope selection the nuclear physics properties; I.e. $Q_{\beta\beta}$, $G^{0\nu}$ and $M^{0\nu}$, the $\beta\beta$ abundance in natural isotopic composition and technical possibilities for isotopic enrichment play a crucial role. The $\beta\beta$ isotopic mass available on the world market and costs are also important especially in the case of future upgrades with larger masses. The chemical properties of the isotopes influence also the choice of technologies used to build the $0\nu\beta\beta$ decay detectors. The spectrum goes from compact solid state detectors (e.g. CUORE, GERDA, COBRA) with high energy resolutions to large volume scintillator detectors (e.g. KamLAND-Zen, SNO+) with poor energy resolutions. Several trends are observed. The technologies used in the new $0\nu\beta\beta$ decay experiments have similarities to those used for other rare-event physics programs (e.g. for dark matter search) leading to synergies. In other cases, detectors that were used in the past for other purposes, were/are upgraded for $0\nu\beta\beta$ decay search (e.g. KamLAND-Zen, SNO+). This saves construction/commissioning time and costs. Finally, the new detector designs often endorse highly efficient background suppression strategies. Beside passive shields made of ultra-radiopure materials, the new experiments often include active shields: The spacial reconstruction of event positions allows to adjust fiducial volume cuts and to reduce unwanted background signals (e.g. EXO-200, KamLAND-Zen, SNO+). The installation of multiple $0\nu\beta\beta$ decay detectors into compact arrays (e.g. CUORE, GERDA, Majorana, COBRA) allows to rule out detector-coincident background signals. Scintillation light produced in cryogenic media used primarily as coolant for semiconductors can be used in anti-coincidence modus with the detectors (e.g. GERDA). The simultaneous detection of the charge signal and the scintillation light of events (e.g. EXO-200, NEXT-100) allows to discriminate background from $0\nu\beta\beta$-like signals. Pulse shape analysis is another powerful tool to recognize surface and multiple-scattered background signals (e.g. GERDA, Majorana, CUORE). Finally, particle tracking with multi-layer detectors allows to define pure samples of $0\nu\beta\beta$-like events and to reconstruct the full kinematics of events (e.g. SuperNEMO, NEXT-100, MOON, DBCA).
The following paragraphs focus on the detectors that have already become operational or will start data collection probably in the next 2 years. A final paragraph is dedicated to recent R&D projects.

EXO-200. This detector is a pressurized time projection chamber (TPC) using liquid xenon as source and detection medium. The xenon is enriched in ^{136}Xe at 81% level and is cooled down with a high-purity heat transfer fluid inside a radiopure copper cryostat. The cylindrical TPC has two wire grids at both ends with different applied voltages leading to a drift field. Behind the grids avalanche photodiodes are installed. Both together they allow to read out simultaneously scintillation light and the charge produced by ionisation, as well as to reconstruct the position of the events.
Based on a first dataset of 121 d lifetime (2012) and a fiducial $\beta\beta$ mass of 79 kg, EXO-200 observed 1(5) events with 1(2)σ around the $Q_{\beta\beta}$ peak region [8]. This was exceptionally low, but still within the background expectations. A half-life limit of $T^{0\nu}_{1/2} > 1.6\times10^{25}$ yr (90% C.L.) was determined. In a second analysis based on a four-fold increased dataset (2014) (31±4) events within 2σ around $Q_{\beta\beta}$ were observed, still compatible with the background model [9]. Thus, $T^{0\nu}_{1/2}$ decreased to $>1.1\times10^{25}$ yr (90% C.L.). Depending on the $M^{0\nu}$ calculation, this corresponds to $\langle m_{\beta\beta}\rangle <(0.19\text{-}0.45)$ eV.

KamLAND-Zen. This experiment is based on an upgrade of the KamLAND detector which has been used mainly for solar neutrino and geo/reactor antineutrino search. The idea was to install a smaller inner balloon containing xenon-loaded scintillator in the center of the large spherical vessel filled with 1000 tons of