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NEUTRINOLESS DOUBLE-BETA DECAY: WHERE WE ARE AND WHERE WE ARE GOING

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Abstract

This short review introduces neutrinoless double-beta decay and discusses the implications of this phenomenon on crucial aspects of particle physics. A critical comparison of the adopted technologies and of their physics reach is performed, illustrating the possible paths towards the next-generation searches that aim at fully covering the inverted-ordering region of the neutrino masses.

1 Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$) is a hypothetical rare nuclear transition (present half-life limits are $\sim 10^{26}$ y) which plays a unique role in understanding fundamental neutrino properties and exploring lepton number violation (LNV). It consists in the transformation of an even-even nucleus into a lighter isobar containing two more protons and accompanied by the emission of two electrons and no other particles, with a change of the total lepton number by two units: $(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^-$. The standard process ($2\nu\beta\beta$), which implies also the emission of two electron antineutrinos, is the rarest nuclear decay and has been observed in eleven nuclei with half-lives in the range $10^{18} - 10^{21}$ y. The detection of the neutrinoless channel would be a major discovery, and would represent the observation of a new phenomenon beyond the Standard Model (SM) of elementary particles, establishing that neutrino is a Majorana particle, rather than a Dirac one as all the other fermions: it would be the only spin-$\frac{1}{2}$ particle to coincide with its own antimatter partner, a possibility left naturally open by its neutrality. In this framework, a new mechanism of mass generation, besides the Higgs mechanism, could be in place for neutrinos explaining naturally the smallness of ordinary neutrino masses, and matter-antimatter asymmetry in the Universe could be accounted for through CP violation in the neutrino sector.

It is important to remark however that, in a beyond-SM perspective, $0\nu\beta\beta$ is much more than a neutrino physics experiment. It is a powerful, inclusive test of LNV, which takes the form of a creation of electrons according to the process $2\mathrm{n} \rightarrow 2\mathrm{p} + 2\mathrm{e}^-$, implemented in nuclear matter. LNV is as important as baryon number violation and naturally incorporated by beyond-SM theories. In this respect, the experimental search for $0\nu\beta\beta$ must be pursued with the highest possible sensitivity irrespectively of the related neutrino-physics scenario, as it is an essential element for a deep comprehension of the elementary constituents of matter and of fundamental interactions.

$0\nu\beta\beta$ can be induced by a plethora of LNV mechanisms. Among them, the so-called mass mechanism – consisting in the exchange of virtual light Majorana neutrinos – occupies a special place, since it is mediated by the light massive neutrinos which undergo flavour oscillations. In this mechanism, the rate of the process is proportional – within an uncertainty due to the computation of the nuclear matrix elements – to the square of the effective Majorana neutrino mass $M_{\beta\beta}$, related to the absolute neutrino mass scale and to the mass ordering. Present limits on $M_{\beta\beta}$ from $0\nu\beta\beta$ are in the range 60-600 meV (the experiment KamLAND-Zen [1]) is leading the field), assuming that the axial charge g_A (the $0\nu\beta\beta$ rate is proportional to ${g_A}^4$) is not quenched and equal to the free nucleon value of ~ 1.25 (the most common approach in the literature). The possible quenching of g_A is an important open issue, since it could reduce even by a factor ~ 4 the sensitivity to $M_{\beta\beta}$. However, this quenching could have no impact on other LNV mechanisms, and in any case it demands for even more powerful technologies and new experimental ideas.

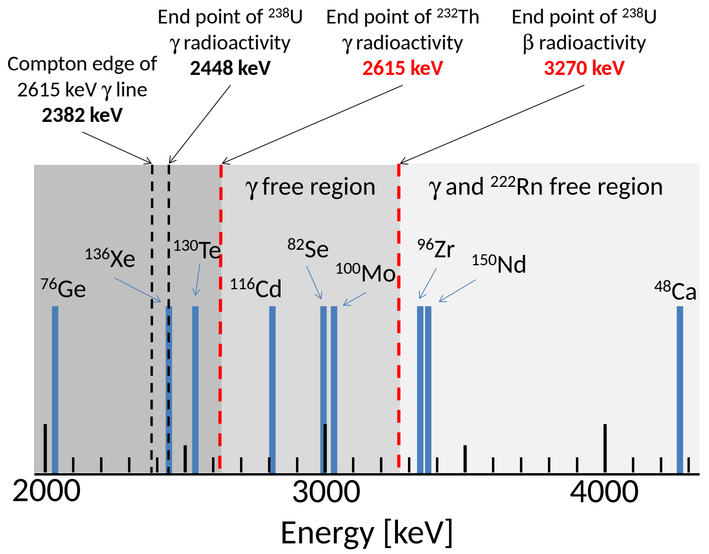

Figure 1: The positions of the expected signals for the nine most favourable $0\nu\beta\beta$ isotopes are compared with background energy markers related to the maximum γ energies of the ^{238}U and ^{232}Th chains and the maximum β energy of the ^{238}U chain.

2 Experimental concepts

In order to observe $0\nu\beta\beta$, experimentalists aim at the detection of the two emitted electrons, which share the total transition energy (the so-called Q-value of the process). The signature of $0\nu\beta\beta$ is therefore a peak at the Q-value in the sum-energy spectrum of the two electrons. The features of the $0\nu\beta\beta$ signal and the long expected life-times suggest immediately the desired properties of a powerful $0\nu\beta\beta$ experiment: large sources and high detection efficiency; high energy resolution; extremely low background (underground operation and high material radiopurity are basic features); viable isotopic enrichment in terms of price and throughput, as the natural isotopic abundance of appealing candidates is generally below 10% (with the exception of ^{130}Te).

In current and future experiments, sources must contain at least tens or hundreds of kg of the isotope of interest. The next frontier is the tonne scale. This constraint makes particularly appealing the so-called calorimetric technique, in which the source is embedded in the detector. Zero background at large exposure scale is a big advantage, as it allows the experimentalists to exploit at best the costly enriched material and detector technology. The Q-value is a crucial criterion, as it affects both the phase space (which approximately scales as $\sim Q^5$) and the background. As a consequence, at the moment only nine isotopes – all with high Q-values – are or may become experimentally relevant. It is instructive to compare their Q-values with two important energy markers in terms of background sources: the 2615 keV marker, a ^{208}Tl line in the ^{232}Th chain, is the end-point of the natural γ radioactivity; the 3270 keV marker is the Q-value of the β decay of ^{214}Bi, belonging to the radon progeny in the ^{238}U chain. A graphical representation is provided in Fig. 1.

A first group of three isotopes (^{76}Ge, ^{130}Te and ^{136}Xe) have a Q-value above 2 MeV but below both markers, and therefore have to cope with the γ background and with the radon-induced one. However, enrichment is viable and superb detection technologies can be employed for these nuclei: germanium diodes (GERDA [2]), xenon liquid and gaseous detectors (EXO [3], NEXT [4]), large liquid scintillator volumes incorporating the candidate nuclei (KamLAND-Zen [1], SNO+ [5]), and TeO_2 bolometers (CUORE [6]). Thus, it is not surprising that the currently most sensitive experiments study these three nuclei (KamLAND-Zen [1], EXO-200 [3], GERDA-I [2] and CUORE-0 [7]), as shown in Fig. 2, which illustrates synthetically the experimental status. Conversely, the three candidates ^{48}Ca, ^{96}Zr and ^{150}Nd are in the best position to carry out a background-free experiment, but they are ruled out in practice by having a very low isotopic abundance and, in addition, large-scale enrichment is impossible or prohibitively expensive. The remaining group of three candidates (^{82}Se, ^{100}Mo and ^{116}Cd) has a $0\nu\beta\beta$ signal out of the reach of the bulk of the γ environmental background and furthermore can be effectively enriched. These three nuclides can be efficiently studied with bolometers. When used in a hybrid version adding a scintillation light readout, like in LUCIFER [8], LUMINEU [9, 10] and AMoRE [11], an almost background-free technology is available.

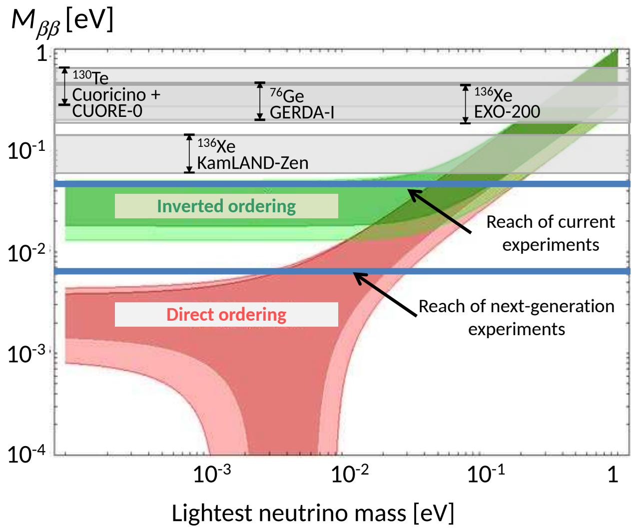

Figure 2: Sensitivities of the current $0\nu\beta\beta$ experiments to $M_{\beta\beta}$ (the span is due to different nuclear models). The reaches of present searches and of next-generation ones are indicatively shown. No g_A quenching is assumed.

3 Critical comparison of the current technologies

The $0\nu\beta\beta$ community (which counts about 850 physicists) is starting to discuss about possible next-generation experiments capable to attack and in prospect fully cover the inverted ordering region, which can only marginally probed by current searches. This goal requires an isotope sensitive mass from hundreds of kg to several tonnes, depending on the adopted technology. Current experiments and ongoing R&D activities suggest that three main routes can allow achieving this objective, depending on the source configuration: we can distinguish searches adopting Fluid-embedded, Crystal-embedded and Externals Source approaches (FS, CS, ES respectively).

3.1 Fluid-embedded Source (FS)

This approach is adopted by the experiments KamLAND-Zen [1)], EXO-200 [3)], NEXT [4)] and SNO+ [5)]. In these searches, either the isotope constitutes by itself the sensitive medium in form of gas or liquid (as ^{136}Xe in EXO-200 and

NEXT – in prospect nEXO and BEXT), or it is dissolved, typically at the level of few %, in a large scintillator volume using pre-existing infrastructures (as ^{136}Xe in KamLAND-Zen and ^{130}Te in SNO+). In both cases, the approach is calorimetric, enabling large efficiencies. The strongest point of this method is that it allows investigating large isotope masses (the 1 tonne scale is well within its reach) and accumulating large statistics. In addition, it is scalable (either by increasing the concentration in case of isotope solution – up to a maximum value dictated by physical limits or light collection efficiency – or by building larger and/or multiples structures in case of Xe as a sensitive medium). High radiopurity is achievable, as fluids are in general easier to purify than the solids adopted in the CS and ES options. However, the radiopurity of the containment structures remains an issue (volume fiducialization is in general necessary, reducing the efficiency in the isotope use), together with radon emanation. Unexpected contamination is always possible, requiring additional purification efforts (see the case of ^{110}Ag in KamLAND-Zen). When the isotope is extremely diluted (as in the case of SNO+ where the isotope/scintillator ratio is a few 10^{-5}), ^{8}B solar neutrinos represent an ultimate irreducible background source. Isotopes used in this approach are the easiest to enrich (^{130}Te has in particular a record natural isotopic abundance of 34% and ^{136}Xe – with its 5-10$/g, has an enrichment cost $\sim$ 10 times lower than the average, even though it is to remark that 1 tonne of enriched Xe corresponds to 1/4 of the world annual Xe production) but have Q-values (2458 keV for ^{136}Xe and 2530 keV for ^{130}Te) below the limit of the natural γ radioactivity (2615 keV of ^{208}Tl). A drawback of ^{136}Xe in particular is the proximity to the Q-value of a line of ^{214}Bi (2448 keV), an isotope belonging to the radon progeny. This situation is aggravated by the general low energy resolution of the FS approach (which makes $2\nu\beta\beta$ a considerable background source): 250 keV FWHM for KamLAND-Zen and 90 keV FWHM for EXO-200. An exception in this scenario is NEXT, which has demonstrated energy resolution around 20 keV FWHM. In terms of background identification, the isotope solution approach can count on event location (and consequent fiducialization) and delayed coincidence. More powerful means are available for the liquid TPC of EXO-200 (multi-site versus single site-events) and especially for NEXT, which – with its high-pressure gaseous TPC – can use event topology as $0\nu\beta\beta$ signature. Finally, we remark that future evolutions of EXO-200 and NEXT could use atomic spectroscopy to identify the final nuclear state by detecting the presence of a ^{130}Ba atom at the event location. In the frame of the FS approach, extensions to multi-tonne scale experiments are already under discussion (nEXO and KamLAND2-Zen).

3.2 Crystal-embedded Source (CS)

This approach is adopted by the experiments GERDA [2], MAJORANA [12], CUORE [7, 6], AMoRE [11] and the demonstrators LUCIFER [8] and LUMINEU [9, 10] in the framework of CUPID [13], the proposed follow-up to the CUORE experiment. In these searches, the isotope is incorporated in high-purity single crystals with a very high mass fraction. As in the FS case, the approach is calorimetric. Here however the efficiency is much higher (80-90%) as no fiducialization is required for background control. In addition, energy resolution is much better than in the FS case (3 keV FWHM for the Ge diodes of GERDA, 5 keV for the TeO_2 bolometers of CUORE and in the range of 5-10 keV for the scintillating bolometers of LUCIFER, LUMINEU and AMoRE). Since the $0\nu\beta\beta$ signal is a peak, high energy resolution is of course welcome. In addition, $2\nu\beta\beta$ is not an issue, with the exception of random coincidences in the ^{100}Mo case (LUMINEU). Scalability is possible, even though achieving the tonne scale and beyond is not as easy as in the FS case. It can be accomplished however thanks to the intrinsic modularity of the CS approach. Crystals have masses of the order of a few kg in the Ge diode case and of 0.3 -1 kg in the bolometric case. Large sensitive masses are achievable by multiplication of the crystal number. Present infrastructures (GERDA and CUORE cryostats) allow housing a few hundreds of kg of isotope mass. The enrichment-purification-crystallization chain, especially in a large-scale context, represents however an important effort in these technologies. Low irrecoverable isotope losses in the crystal production processes are crucial, and have been demonstrated only for ^{76}Ge, ^{100}Mo and ^{116}Cd up to now. The rather low Q-value of ^{76}Ge (2039 keV) reduces the phase space for the $0\nu\beta\beta$ transition and makes background control harder, as several characteristic-energy photons of the natural γ radioactivity contributes to the background. In the bolometric case, only the 2615 keV line of ^{208}Tl is relevant for ^{130}Te (CUORE case) and no major lines contributes in the scintillating bolometer case, where the involved isotopes have a Q-value above 2615 keV (3034 keV for ^{100}Mo – LUMINEU and AMoRE – and 2998 keV for ^{82}Se – LUCIFER). Specific technologies for background control are available. In case of Ge diodes, pulse shape discrimination can reject multisite events generated by external γ's. By exploting this method and with the help of an active liquid-argon veto, outstanding results were recently obtained in terms of specific background by GERDA-II [14]: a record value of the order of 7×10^{-4} counts/(keV kg y). In case of bolometers, a simultaneous measurement of scintillation and heat can reject very efficiently the dominant α background in detectors based on ZnSe (LUCIFER), $ZnMoO_4/Li_2MoO_4$ (LUMINEU) and $CaMoO_4$ (AMoRE) crystals. This discrimination can be performed with higher difficulty in the non-scintillating TeO_2 crystals, using Cherenkov light. All the isotopes involved in the SC approach can be enriched by centrifugation, with costs which range from $\sim$ 20 \$/g of ^{130}Te to 80-120 \$/g in the other cases. In the frame of the CS approach, extensions to scales of several hundreds of kg or $\sim$ 1 tonne are under discussion (GERDA upgrade in Gran Sasso, CUPID, and joint GERDA-MAJORANA experiment).

3.3 External Source (ES)

The only experiment beyond the R&D phase which plans to use the ES approach is SuperNEMO [15], which will be preceded by a small-scale demonstrator under commissioning. The enriched source, consisting of a thin foil (thickness $\sim$ 50 mg/cm^2) containing 7 kg of ^{82}Se in the demonstrator, is separated from the detecting section, which comprises a gas tracker and a plastic-scintillator calorimeter. The strong points of this technique are the compatibility with all the isotopes and the full topological reconstruction of the events, providing excellent background rejection. In addition, the sensitivity to the Majoron mode is unrivalled. Drawbacks are the low efficiency (30%) and energy resolution (120 keV FWHM). Scalability is possible by replication of $\sim$ 5 kg modules, but with high cost and space occupation. The low efficiency could be partially compensated by the use of the ^{150}Nd, which has the highest phase space and potentially zero background because of the very high Q-value (3371 keV). Recently, the enrichment of this isotope by high-temperature centrifuges was demonstrated, but the cost remains very high.

4 Conclusions

We have shown in this review that the experimental search for $0\nu\beta\beta$ is a rich and living field. A healthy competion between different technologies is pushing forward the reach of the current and future experiments. On a two-three year time scale, several searches will start to explore the inverted-ordering region of the neutrino mass pattern. On a longer time scale, we could have two – three experiments capable of fully covering this region and to approach the direct-ordering one.

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