Double Beta Decay Searches

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Abstract. Neutrinoless double beta decay is one of the most sensitive probes for the regime of physics beyond the standard model. It can provide fundamental information on the character of neutrinos and on their absolute mass scale. The present status of experiments searching for neutrinoless double-beta decay ($\beta\beta(0\nu)$) is reviewed. Given the observation of neutrino oscillations and the present knowledge of neutrino masses and mixing parameters, a possibility to observe $\beta\beta(0\nu)$ at a neutrino mass scale in the range 10-50 meV could actually exist. This is a real challenge faced by a number of new proposed projects. The most important parameters contributing to the experimental sensitivity are outlined. A short discussion on nuclear matrix element calculations is also given.

1. Introduction

First suggested by M.Goeppert-Mayer in 1935, Double Beta Decay (DBD) is a rare spontaneous nuclear transition in which the charge of two nuclei belonging to the same isobaric multiplet changes by two units with the simultaneous emission of two electrons. In order to avoid (or at least inhibit) the occurrence of the equivalent sequence of two single beta decays, it is generally required that both the parent and the daughter nuclei be more bound than the intermediate one. Because of the pairing term, such a condition is fulfilled in nature for a number of even-even nuclei. The decay can then proceed both to the ground state or to the first excited states of the daughter nucleus. Double beta transitions accompanied by positron emission or electron capture are also possible. However they are usually characterized by poorer experimental sensitivities and will not be discussed in the following. We refer to the most recent reviews on $\beta\beta$ for a more complete treatment on the subject[2].

Among the possible $\beta\beta$ modes two are of particular interest, the $2\nu$ mode ($\beta\beta(2\nu)$) $\frac{A}{2}X \rightarrow \frac{A}{2} X + 2e^- + 2\bar{\nu}$, which observes the lepton number conservation and it is allowed in the framework of the Standard Model (SM) of electro-weak interactions, and the $0\nu$ mode ($\beta\beta(0\nu)$) $\frac{A}{2}X \rightarrow \frac{A}{2+2} X + 2e^- + 2\nu$ which violates the lepton number by two units. A third decay mode ($\beta\beta(0\nu,\chi)$) in which one or more neutral bosons $\chi$ (Majorons) are emitted $\frac{A}{2}X \rightarrow \frac{A}{2+2} X + 2e^- + N\chi$ is also often considered. The interest in this decay is mainly related to the existence of Majorons, massless Goldstone bosons that arise upon a global breakdown of B–L symmetry.

From the point of view of Particle Physics $\beta\beta(0\nu)$ is of course the most interesting of the $\beta\beta$ decay modes. In fact, after 70 years from its introduction by W.H. Furry[3], $\beta\beta(0\nu)$ is still one of the most powerful tools to test neutrino properties: it can exist only if neutrinos are Majorana particles and it allows then to fix important constraints on the neutrino mass scale.
In all envisaged decay modes, \( \beta\beta(0\nu) \) rate is usually expressed as \[
\frac{1}{T_{12}} = G^{0\nu}\left| M^{0\nu}(2) \right|^2 \langle m_\nu \rangle^2,
\]
where \( G^{0\nu} \) is the (exactly calculable) phase space integral, \( |M^{0\nu}(2)|^2 \) is the nuclear matrix element and \( \langle m_\nu \rangle \) is a combination of the neutrino mass eigenvalues \( \langle m_\nu \rangle \equiv \sum_{k=1}^{3} |\mu_{ek}|^2 m_k e^{i\alpha_k} \) which, in the limit of small neutrino masses becomes \( \langle m_\nu \rangle = c_1^2 c_3^2 m_1 + s_1^2 s_3^2 m_2 + s_1 s_3 c_2^2 m_3 \).

Unfortunately, the presence of the Majorana phases \( \alpha_k \) in the \( \langle m_\nu \rangle \) expression implies that cancellations are possible. Such cancellations are complete for a Dirac neutrino since it is equivalent to two degenerate Majorana neutrinos with opposite CP phases. This stresses once more the fact that \( \beta\beta(0\nu) \) can occur only through the exchange of Majorana neutrinos. It should be also pointed out that \( \beta\beta(0\nu) \) represents the unique possibility to measure the neutrino Majorana phases.

Given the evidence for neutrino oscillations and the present knowledge of neutrino masses and mixing parameters, two possible orderings are possible (neutrino mass hierarchy problem). In the case that forthcoming \( \beta\beta(0\nu) \) experiments would not observe any decay (and assuming that neutrinos are Majorana particles) the inverse ordering could finally be excluded thus fixing the problem of the neutrino absolute mass scale[4, 5].

\( \langle m_\nu \rangle \) is actually the only \( \beta\beta(0\nu) \) measurable parameter containing direct information on the neutrino mass scale. Unfortunately its derivation from the experimental results on \( \beta\beta(0\nu) \) half-lifetimes requires a precise knowledge of the transition Nuclear Matrix Elements \( M^{0\nu}(\text{NME}) \). Many (often conflicting) evaluations are available in the literature leading to large uncertainty ranges for \( \langle m_\nu \rangle \). This has been recognized as a critical problem by the \( \beta\beta \) community. New efforts have been therefore recently directed to its solution: new calculations based on different methods and various cross-checks to improve the reliability of these calculations are presently being undertaken[6, 7, 8]. A statistical analysis of the NME calculation results according to different methods and model parameters has also been considered[9].

2. Experimental approaches: present status

The only experimentally available informations in \( \beta\beta(0\nu) \) are those carried by the daughter nucleus and the two emitted electrons. Different signatures depend therefore on the number of such informations which are actually measured: sum of the electron energies, single electron energy and angular distributions, identification and/or counting of the daughter nucleus. A better signature is often synonymous of a lower background and, definitely, of a better sensitivity. All experiments tend therefore to find a compromise between the desire to collect the maximum number of informations and the best way in which such a goal can be accomplished. Two main general approaches have been followed so far for \( \beta\beta \) experimental investigation: i) indirect or inclusive methods, and ii) direct or counter methods. Inclusive methods are based on the measurement of anomalous concentrations of the daughter nuclei in properly selected samples, characterized by very long accumulation times. They include Geochemical and Radiochemical methods which, being completely insensitive to different \( \beta\beta \) modes, can only give indirect evaluations of the \( \beta\beta(0\nu) \) and \( \beta\beta(2\nu) \) lifetimes. They have played a crucial role in \( \beta\beta \) searches especially in the past.

Counter methods are based instead on the direct observation of the two electrons emitted in the decay. Different experimental parameters (energies, momenta, topology, etc) can then be registered according to the different capabilities of the employed detectors. These methods are further classified in inhomogeneous (when the observed electrons originate in an external sample) and homogeneous experiments (when the source of \( \beta\beta \) 's serves also as detector).

In most cases the various \( \beta\beta \) modes are separated just on the base of the different distribution expected for the electron sum energies: a continuous bell distribution for \( \beta\beta(2\nu) \) and \( \beta\beta(0\nu, \chi) \), and a sharp line at the transition energy for \( \beta\beta(0\nu) \). Direct counting experiments with very good energy resolution are presently the most attractive approach for \( \beta\beta(0\nu) \) searches.
Experimental evidence for several $\beta\beta(2\nu)$ decays has been provided using the measured two-electron sum energy spectra, the single electron energy distributions and the event topology. On the other hand, impressive progress has been obtained during the last years also in improving $\beta\beta(0\nu)$ half-life limits for a number of isotopes. The best results are still maintained by the use of isotopically enriched HPGe diodes for the experimental investigation of $^{76}\text{Ge}$ (Heidelberg-Moscow[10] and IGEX[11]) but two other experiments have recently reached comparable sensitivities: NEMO3[12, 13] at LSM and CUORICINO at LNGS[14]. The former is a large inhomogeneous detector aiming at overcoming the intrinsic limits of the technique (relatively small active masses) by expanding the setup dimensions; the big advantage of the NEMO3 technique is the possibility to access single electron informations. CUORICINO is, on the other hand, a TeO$_2$ granular calorimeter based on the bolometric technique; it aims at exploiting the excellent performance of the bolometers (and the possibility they offer to be built with any material of practical interest[15, 16]) to scan the most interesting $\beta\beta(0\nu)$ active isotopes. NEMO3 will continue data taking until the end of 2010 while CUORICINO was stopped in June 2008 to be substituted by CUORE-0, the first tower of CUORE. The NEMO3 effort to cover as many as possible $\beta\beta$ nuclei thus allowing a diret check for $\beta\beta(2\nu)$ NME elements is evident (Tab. 1).

The evidence for a $\beta\beta(0\nu)$ signal has also been claimed (and recently confirmed [17] by a small subset (KHDK) of the HDM collaboration at LNGS with $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y. The result is based on a re-analysis of the HDM data. Such a claim has raised some criticism but cannot be dismissed out of hand. On the other hand, none of the existing experiments can rule it out, and the only certain way to confirm or refute it is with additional sensitive experiments. In particular, next generation experiments should easily achieve this goal.

**Table 1.** Best reported results on $\beta\beta$ processes. $\beta\beta(0\nu)$ limits are at 90% CL while $\beta\beta(2\nu)$ results are averaged values, taken from ref.[18] Except when explicitly noted $\beta\beta(2\nu)$ results are taken from ref.[18]. Future developments of the technique are shown in the last columns together with their expected location and isotope mass.

| Isotope | $T_{1/2}^{2\nu}$ (10$^{19}$y) | $T_{1/2}^{0\nu}$ (10$^{24}$y) | Future Experiment | Mass (kg) | Lab |
|---------|-------------------------------|-----------------------------|-------------------|----------|-----|
| $^{48}$Ca | (4.2$^{+2.1}_{-1.0}$) | > 0.0014[19] | CANDLES | OTO | |
| $^{76}$Ge | (150 ± 10) | > 19[10] | GERDA | 18-40 | LNGS |
| | | 22.3$^{+4.4}_{-3.3}$[17] | | | |
| | | > 15.7[11] | MAJORANA | 60 | SUSEL |
| $^{82}$Se | (9.6 ± 1.0)[13] | > 0.36[13] | SuperNEMO | 100 | LSM |
| $^{90}$Zr | (2.35 ± 0.21)[13] | > 0.0092[13] | | | |
| $^{100}$Mo | (0.711 ± 0.054) | > 1.1[13] | MOON | | |
| $^{116}$Cd | (2.8 ± 0.3) | > 0.17[20] | | | |
| $^{130}$Te | (69 ± 13.4)[13] | > 2.94 | CUORE | 204 | LNGS |
| $^{136}$Xe | > 81[21] | > 0.12[22] | EXO | 160 | WIPP |
| $^{150}$Nd | (0.911 ± 0.067)[13] | > 0.0036[23] | SNO+ | 56 | SNOLAB |

3. Forthcoming experiments
The performance of the different $\beta\beta(0\nu)$ experiments is usually expressed in terms of an experimental sensitivity or detector factor of merit, defined as the process half-life corresponding to the maximum signal $n_B$ that could be hidden by the background fluctuations at a given
statistical C.L. At 1σ level ($n_B = \sqrt{B T M \Delta}$), one obtains:

$$F_{0\nu} = \frac{\tau_{1/2}^{Back,Fluct.}}{n_B} = \ln 2 \frac{N_{\beta\beta} \epsilon}{n_B} = \ln 2 \times \frac{x \eta \epsilon N_A}{A} \sqrt{\frac{M T}{B \Delta}}$$

(68% CL)

where $B$ is the background level per unit mass and energy, $M$ is the detector mass, $T$ is the measure time, $\Delta$ is the FWHM energy resolution, $N_{\beta\beta}$ is the number of $\beta\beta$ decaying nuclei under observation, $\eta$ their isotopic abundance, $N_A$ the Avogadro number, $A$ the compound molecular mass, $x$ the number of $\beta\beta$ atoms per molecule, and $\epsilon$ the detection efficiency.

Despite its simplicity, equation (1) has the unique advantage of emphasizing the role of the essential experimental parameters: mass, measuring time, isotopic abundance, background level and detection efficiency. Most of the criteria to be considered when optimizing the design of a new $\beta\beta(0\nu)$ experiment follow directly from it: i) a well performing detector (e.g. good energy resolution and time stability) giving the maximum number of informations (e.g. electron energies and event topology); ii) a reliable and easy to operate detector technology requiring a minimum level of maintenance (long underground running times); iii) a very large (possibly isotopically enriched) mass, of the order of one ton or larger; iv) an effective background suppression strategy.

Unfortunately, these simple criteria are often conflicting and simultaneous optimisation is rarely possible.

Calorimetric detectors are usually preferred since they have produced so far the best results. The calorimetric approach suffers however from a strong limitation: it can be applied only to a small number of $\beta\beta(0\nu)$ isotopes (e.g. $^{76}$Ge, $^{136}$Xe, $^{48}$Ca), thus limiting the number of experimentally accessible isotopes. As suggested by the NEMO3 and CUORICINO experience however, a possible way out exists.

A series of new proposals has been boosted in recent years by the renewed interest in $\beta\beta(0\nu)$ following neutrino oscillation results. The ultimate goal is to reach sensitivities such to allow an investigation of the inverse hierarchy (IH) of neutrino masses ($\langle m_\nu \rangle \sim$10-50 meV). From an experimental point of view this corresponds however to active masses of the order of 1 ton with background levels of the order of 1 c/keV/ton/y. A challenge that can hardly be faced by the current technology. Phased programs have been therefore proposed in USA and Europe[24, 25].

Second generation experiments are all characterized by hundred kg detectors and 1-10 c/kev/ton background rates. Their goal is to select the best technology and approach the IH region.

A list of some of the forthcoming $\beta\beta(0\nu)$ projects is given in table 1. They can be classified in three broad classes: i) dedicated experiments using a conventional detector technology with improved background suppression methods (e.g. GERDA, MAJORANA); ii) experiments using unconventional detector (e.g. CUORE) or background suppression (e.g. EXO, SuperNEMO) technologies; iii) experiments based on suitable modifications of an existing setup aiming at a different search (e.g. SNO+, KAMLAND). In some cases technical feasibility tests are required, but the crucial issue is still the capability of each project to pursue the expected background suppression. Although all proposed projects show interesting features for a second generation experiment, only few of them are characterized by a reasonable technical feasibility within the next few years.

MAJORANA and GERDA are both phased programs representing large scale extensions of past successful experiments on $^{76}$Ge $\beta\beta(0\nu)$.

Evolved from the HM experiment, GERDA[26] aims at implementig the concept of Ge diodes immersed in a LAr bath[27] for a radical background suppression. The GERDA setup construction is presently being completed in Gran Sasso. 18 and 40 kg of Germanium detectors enriched in $^{76}$Ge are foreseen for the first and second phase respectively. GERDA-I will scrutinize
the KHDK claim starting in 2010 and reaching a sensitivity $T_{1/2} > 2 \times 10^{25}$ y (90 % CL) after two years of data taking. 40 kg of germanium isotopically enriched in $^{76}$Ge are already available for GERDA-II. A large part of the efforts are presently directed to develop the segmented detectors crucial for the targeted $10^{-3}$ c/keV/kg background level. The expected 5y sensitivity is $\sim 2.5 \times 10^{26}$ y. Depending on the physics results of the previous phases, a third phase using 500 to 1000 kg of enriched germanium detectors is planned, merging GERDA with the US lead Majorana collaboration.

MAJORANA, a mainly USA proposal with important Canadian, Japanese, and Russian contributions, is an evolution of the IGEX experiment. The proposed initial configuration[28] would consist of 171 segmented n-type germanium crystals (180 kg), distributed in 3 independent ultra-clean electro-formed conventional cryostats of 57 crystals each. The whole assembly would be enclosed in a low-background passive shield and active veto and be located deep underground. A 60 kg demonstrator (single cryostat) is presently being developed to demonstrate the viability of the technique. The completion of this phase is expected in 2014.

CUORE[29] (Cryogenic Underground Detector for Rare Events) is a very large extension of the TeO$_2$ bolometric array concept pioneered by the Milano group at the Gran Sasso Laboratory since the eighties. CUORE will consist of a rather compact cylindrical structure of 988 cubic natural TeO$_2$ crystals of 5 cm side (750 g), arranged into 19 separated towers (13 planes of 4 crystals each) and operated at a temperature of 10 mK. The expected energy resolution is $\sim 5$ keV FWHM at the $\beta\beta(2\nu)$ transition energy ($\sim 2.53$ MeV). A background level of of the order of $\sim 0.01$ c/keV/kg/y is expected by extrapolating the CUORICINO background results and the dedicated CUORE R&D measurements. The expected 5y sensitivity is $2.1 \times 10^{26}$ y. CUORE will therefore allow a close look at the IH region of neutrino masses. CUORE is fully funded and presently under construction at LNGS at a relatively low cost thanks to the high natural abundance of $^{130}$Te. Setup completion is expected in 2012. Thanks to the bolometer’s versatility, alternative options with respect to TeO$_2$ are also possible. In particular, promising results have been recently obtained with scintillating bolometers[30] which could allow to study in the future new $\beta\beta(0\nu)$ active isotopes with improved sensitivity.

EXO[31] (Enriched Xenon Observatory) is a challenging project based on a large mass ($\sim 1–10$ tons) of isotopically enriched (85% in $^{136}$Xe) Xenon. An ingenious tagging of the doubly charged Ba isotope produced in the decay ($^{136}$Xe $\rightarrow ^{136}$Ba$^{++} + 2e^-$) would allow an excellent background suppression. The technical feasibility of such an ambitious project aiming at a complete suppression of all the backgrounds requires a hard, still ongoing R&D phase. The unavoidable $\beta\beta(2\nu)$ contribution is a serious concern due to the poor energy resolution of Xe detectors. A smaller prototype experiment with a Xe mass of 200 kg (80% $^{136}$Xe), is presently being installed at WIPP. The prototype has no barium tagging. The primary goal is to measure $^{136}$Xe $\beta\beta(2\nu)$ and to study $\beta\beta(0\nu)$ with a sensitivity of $\sim 10^{25}$ y in two years of data taking.

The proposed Super-NEMO experiment is the only based on an inhomogeneous approach. It is an extension of the NEMO3 concept, properly scaled in order to accommodate $\sim 100$ kg of $^{82}$Se foils spread among 20 detector modules. The proposed geometry is planar. The energy resolution will be improved from 12% FWHM to 7% FWHM to improve the signal detection efficiency from 8% to 40% and reduce the $\beta\beta(2\nu)$ contribution. The detector modules will have an active water shield to further reduce cosmic ray backgrounds. The proposed detector dimensions will require a larger hall than is currently available at Frejus and an expansion of the facility is therefore required and actively pursued. A demonstrator (single module) is presently fully funded to be completed in 2011 with a test run in the current NEMO3 site. If funded, Super-NEMO construction should immediately start.

New developments have been recently proposed concerning the possibility to disperse $\beta\beta(0\nu)$ active isotopes in large masses of low-activity scintillators. SNO+ is pursuing the goal of studying $^{150}$Nd with 50 to 500 kg of isotopically enriched Neodium depending on the results
of the currently ongoing R&D program.

A similar approach is proposed by KAMLAND, but for $^{136}$Xe. Their program should start in 2011 (first phase) with 200-400 kg of isotope and continue in 2013 with 1 ton of Xenon enriched to 90\% in $^{136}$Xe. A preliminary estimate of the 5y sensitivity for phase I amounts to $\sim 10^{26}$ y.

4. Conclusions
A renewed interest in $\beta\beta(0\nu)$ searches has been stimulated by neutrino oscillation results. Neutrinoless $\beta\beta$ is finally recognized as a unique tool to measure neutrino properties (nature, mass scale, intrinsic phases) unavailable to the other neutrino experiments. Present $\langle m_\nu \rangle$ sensitivities are still outside the range required to test the inverted neutrino mass hierarchy. An international effort is however supporting a phased $\beta\beta(0\nu)$ program based on a number of newly proposed experiments to pursue such a goal. The success of such a program strongly depends on the true capability of the proposed projects to reach the required background levels in the $\beta\beta$ region. The claimed evidence for a $\beta\beta(0\nu)$ signal in the HM data could be soon verified by the presently running experiments and in any case, by the forthcoming next generation experiments.

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