# PRESENT AND FUTURE OF NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENTS

**P. Gorla**

*Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare, Assergi, Italy*

Neutrinoless Double Beta Decay (0νDBD) is a rare spontaneous nuclear transition that plays a crucial role in neutrino physics as it can give information on the neutrino nature and neutrino mass scale. The experimental signature in the case of 0νDBD is in principle very clear: one should expect a peak at the transition energy of the decay in the summed two-electron energy spectrum. In spite of such characteristic, its identification is very challenging as the number of expected events is really low and the peak could be hidden by radioactive background fluctuations. I will discuss which experimental approaches can be followed to search for 0νDBD, which decay sources could be used and which are the important experimental parameters to take into account to realize a powerful 0nDBD experiment. Recently many experiments aiming to observe the 0νDBD have been proposed. The state of art, the next generation experiments and possible future scenarios in the experimental 0νDBD community will be reported.

## 1. Introduction

In the last ten years, several neutrino oscillation experiments have confirmed that neutrino mass eigenvalues are different from zero [1]. The evidence of a neutrino rest mass represents one of the most exciting discoveries in the field of particle physics. In this scenario some crucial information to complete the neutrino knowledge puzzle are still missing: the Dirac or Majorana nature of the neutrino and its absolute mass scale. The discovery of the 0νDBD, however, will provide not only the ultimate answer about the nature of the neutrino, but will also offer a sensible tool to measure its mass. The focusing interest on 0νDBD search came together with the increasing awareness of the challenge of pushing the sensitivity of experiments to the allowed regions of mass. Present generation experiments are designed, besides checking the Heidelberg-Moscow evidence (HM-KK) [2], to start exploring the Inverse Hierarchy (IH) mass region. Next generation will probably rule out the IH region. If no evidence of 0νDBD is found, pushing further the sensitivity of the experiments will need the introduction of new ideas.

After a brief overview of the physics of Double Beta Decay (Section 2), the experimental approaches and results of 0νDBD experiments are discussed (Section 3). In Section 4 a review of present generation experiments, with status and expected sensitivities, is presented. In the final Section some considerations on possible future scenarios are exposed.

## 2. Neutrinoless Double Beta Decay

Two-neutrino Double Beta Decay (2νDBD) is expected to occur in the Standard Model as a second order effect, and it imposes no special requirements on the properties of the neutrino. It will occur irrespective of whether the neutrino is a Majorana or a Dirac particle and irrespective of whether it has a mass or not. This process, suggested by M. Goeppert-Mayer in 1935 [3], is a rare spontaneous nuclear transition in which an initial nucleus (A, Z) decays to a member (A,Z+2) of the same isobaric multiplet with the simultaneous emission of two electrons. 2νDBD is a second order transition, resulting in an extremely slow decay rate, namely the slowest process ever observed in nature, with typical life times of the order of $10^{18}$ - $10^{22}$ y. The observation of such a rare process is possible only if the occurrence of the equivalent sequence of two single beta decays is prohibited or strongly suppressed. The typical case is when both the parent and the daughter nuclei are 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. Double beta transitions accompanied by positron emission or electron capture are also possible. However they are usually characterized by lower transition energies and poorer experimental sensitivities and they will not be discussed in the following. A more complete treatment on the subject can be found in [4].

More interesting for neutrino physic is 0νDBD, first proposed by W.H. Furry [5] in 1939. In this case there is the maximum lepton number violation ($\Delta L = 2$) and the decay is, therefore, not allowed by the Standard Model. The 0νDBD can occur only if two requirements are satisfied: i) the neutrino has to be a Majorana particle, and ii) the neutrino has to have a non-vanishing mass. The second condition is needed because of the helicity of the neutrino. Due to the V - A nature of the weak interaction, the neutrino emitted in the first vertex is right handed, while in order to be absorbed in the second one, it needs to change its helicity. Thanks to the finite mass this is possible, with a probability $m_\nu / E_\nu$ ; from here it turns out that the amplitude of the decay is proportional to $m_\nu$. Disregarding more unconventional contributions (SUSY or left-right symmetric models), the 0νDBD rate is usually expressed as:

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} |M^{0\nu}|^2 |<m_\nu>|^2, \quad (1)$$

where $G^{0\nu}$ is the (exactly calculable) phase space integral $Q_{\beta\beta}{}^5$ ($Q_{\beta\beta}$ represents the Q-value of the decay), $|M^{0\nu}|$ is the specific nuclear matrix element of the nucleus undergoing the decay and $<m_\nu>$ is a combination of the neutrino mass eigenvalues:

$$|<m_\nu>| \equiv | |U_{11}|^2 m_1 + |U_{12}|^2 m_2 {}^{ei\varphi 2} + |U_{13}|^2 m_3 e^{i\varphi 3}|, \quad (2)$$

where $e^{i\varphi j}$ are the Majorana CP phases (= ±1 in case of CP conservation), $m_j$ the mass eigenvalues and $U_{ji}$ the matrix elements of the Pontecorvo - Maki - Nagakawa-sackata (PMNS) matrix. The presence of the $\varphi_k$ phases implies that cancellations are, unfortunately, 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 0νDBD can occur only through the exchange of Majorana neutrinos.

From a Particle Physics point of view, 0νDBD represents a unique tool in order to measure the neutrino Majorana phases and to assess the absolute scale of the neutrino masses. As in evidence from Eq. (1), the derivation of the crucial parameter $<m_\nu>$ from the experimental results on 0νDBD lifetime requires a precise knowledge of the Nuclear Matrix Elements (NME) of the transition. Unfortunately, this is not an easy job, and a definite knowledge of NME values and uncertainties is still lacking in spite of the large attention attracted by this area of research. A detailed review of this complex topic is beyond the purpose of this paper and can be found in [6].

## 3. Experimental approaches

The daughter nucleus and the two emitted electrons carry the only experimentally available information in 0νDBD. Different signatures depend therefore on which parameter of these out coming products is 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 information and the best way in which such a goal can be accomplished.

Modern DBD detectors are usually classified in inhomogeneous, when the observed electrons originate in an external sample, and homogeneous, when the source of DBD serves also as detector. In most cases the various DBD modes are separated just on the base of the different distribution expected for the electron sum energies: a continuous bell distribution for 2νDBD, and a sharp line at the transition energy for 0νDBD. Homogeneous experiments with very good energy resolution are presently the most attractive approach for 0νDBD searches. Experimental evidence for several 2νDBD decays has been provided using the measured two-electron sum energy spectra, the single electron energy distributions and the event topology. During the last years an impressive progress has been obtained in improving 0νDBD 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 $^{76}$Ge (Heidelberg-Moscow [2] and IGEX [7]) but two other experiments have recently reached comparable sensitivities: NEMO3 [8] at LSM and CUORICINO at LNGS [9]. The former is a large tracking calorimeter detector where the 2 electrons emitted by a thin foil of DBD emitter (e.g. $^{100}$Mo) are first tracked and then energy measured. The big advantage of the NEMO3 technique, despite the relatively smallness of the source mass, is the possibility to access single electron. CUORICINO is, on the other hand, a $TeO_2$ array of bolometers; exploiting the excellent energy resolution of these detectors to identify the 0νDBD peak of $^{130}$Te. NEMO3 will continue data taking until the end of 2010 while CUORICINO was stopped in June 2008, after a 6 years activity.

Evidence for a 0νDBD signal has also been claimed [2] by a small subset of the Heidelberg Moscow collaboration (HD-KK) at LNGS with $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ y. The result is based on a re-analysis of the HM 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.

## 4. Next generation

The performance of the different 0νDBD 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 ($n_B = (bT\, M\, \Gamma)^{1/2}$), one obtains:

$$F_{0\nu} = \ln 2 \cdot N_{\beta\beta} \cdot \varepsilon \cdot \frac{T}{n_B} = \ln 2 \cdot \frac{x \cdot \eta \cdot \varepsilon \cdot N_A}{A} \sqrt{\frac{M \cdot T}{b \cdot \Gamma}} \quad (68\ \%\ \text{C.L.}), \qquad (3)$$

where b is the background level per unit mass and energy, M is the detector mass, T is the measure time, Γ is the FWHM energy resolution, $N_{\beta\beta}$ is the number of DBD nuclei under observation, η their isotopic abundance, $N_A$ the Avogadro number, A the compound molecular mass, x the number of ββ atoms per molecule, and ε the detection efficiency. In the case in which the background level B is so low that the expected number of background events in the region of interest along the experiment life is of order of unity: ("zero background" (0B) experiments) equation (3) assumes a simplified form in which the finale square root is substituted by $MT/n_L$ where $n_L$ is a constant depending on the chosen CL and on the actual number of observed events.

Despite its simplicity, equation (3) 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 0νDBD experiment follow directly from it: i) a well performing detector (e.g. good energy resolution and time stability) giving the maximum information (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 optimization is rarely possible. Missing information in equation (3) is the estimation of cost. In the beyond-ton-scale generation of experiments the cost will be one of the leading parameters in the choice of the experimental strategies. Several figures of merit, such as $\ln(F^{0\nu})$/M$, have been proposed and will be applied to the proposed experiments. A final comment must be added regarding energy resolution. Despite in the 0B experiments sensitivity formula, Γ does not appear as a relevant parameter, the possibility of distinguishing the 0νDBD peak from the intrinsic 2νDBD background force to consider it a as a crucial parameter.

The ultimate goal of present effort for the 0νDBD community is to reach sensitivities such to allow an investigation of the IH of neutrino masses ($\langle m_\nu \rangle \approx$ 10 - 50 meV). From an experimental point of view this corresponds to active masses of the order of 1 ton with background levels of the order of 1 c/keV/ton/y. This is a challenge that can hardly be faced by the current technology. 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 0νDBD projects is given in the Table. 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.

**Candidate isotope, masses, and sensitivity for 5y run of the proposed 0νDBD experiment**

| Isotope | $T^{0\nu}_{1/2}$ ($10^{25}$ y) in 5 y | Future experiment | Mass | Lab |
|---|---|---|---|---|
| $^{76}$Ge | 2 (2y) | GERDA-I [16] | 18 | LNGS |
| | 25 | GERDA-II | 40 | |
| | | Majorana | 60 | SUSEL |
| $^{82}$Se | 3 | SuperNEMO [13] | 100 | LSM |
| | | Lucifer [11] | 40 | |
| $^{96}$Zr | | SuperNEMO | | LSM |
| $^{130}$Te | 21 | CUORE [10] | 740 | LNGS |
| $^{136}$Xe | 10 (2 y) | EXO-I [12] | 200 | Wipp |
| | 250 | EXO-II [12] | 1000 | |
| | 10 | KamLAND [15] | 1000 | Kamioka |
| $^{150}$Nd | 10 | SNO+ [14] | 500 | SNOLAB |

MAJORANA and GERDA are both phased programs representing large-scale extensions of past successful experiments on $^{76}$Ge 0νDBD. The GERDA setup, evolved from HM detectors, is presently being completed in Gran Sasso. GERDA-I will scrutinize the HD-KK claim starting in 2010 and reaching a sensitivity $T_{1/2} > 2 \cdot 10^{25}$ y (90 % CL) after two years of data taking. GERDA-II will include segmented detectors, presently under development, crucial for the targeted 0.001 c/keV/kg background level. The expected 5 y sensitivity is $\approx 2.5 \cdot 10^{26}$ y. A third phase using 500 to 1000 kg of enriched germanium detectors is planned, merging GERDA with the Majorana collaboration. MAJORANA is an evolution of the IGEX experiment. A 60 kg demonstrator is presently being developed to demonstrate the viability of the technique. The completion of this phase is expected in 2014.

CUORE [10] (Cryogenic Underground Detector for Rare Events) is a ton-scale extension of the $TeO_2$ bolometric array concept pioneered by the Milano and Gran Sasso groups at LNGS since the eighties. CUORE will consist of a cylindrical structure of 988 cubic natural TeO2 crystals of 5 cm side (750 g). The expected energy resolution is ≈5 keV FWHM at the 0νDBD transition energy (2527 keV). A background level of the order of ≈0.01 c/keV/kg/y is expected by extrapolating the CUORICINO background results and the dedicated CUORE R&D measurements. The expected 5 y sensitivity is $2.1 \cdot 10^{26}$ 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. Setup completion is expected in 2012. Bolometer's versatility is nowadays opening the way to future high sensitivity projects. The Lucifer experiment, based on the idea of using scintillating bolometers for discriminating the different radiation origin of heat signals trough the different light emission, besides being a competitive standalone experiment is an interesting a R&D for a possible CUORE Next sub-meV sensitivity bolometric experiment [11]. EXO [12] (Enriched Xenon Observatory) is a challenging project based on a large mass (≈ 1 - 10 tons) of isotopically enriched (85 % in $^{136}$Xe) Xenon. An ingenuous tagging of the doubly charged Ba isotope produced in the decay ($^{136}$X e $\rightarrow$ $^{136}Ba^{++} + 2e^-$) would allow excellent background suppression. The technical feasibility of such an ambitious project is still in an R&D phase. The unavoidable 0νDBD contribution is a serious concern due to the poor energy resolution of Xe detectors. EXO-I, with no Ba tagging, is a prototype with a Xe mass of 200 kg (80 % 136 Xe), presently installed at WIPP. The expected sensitivity on 0νDBD is ≈$10^{25}$ y in two years of data taking. The proposed Super-NEMO [13] experiment is an extension of the successful NEMO3 concept, properly scaled in order to accommodate ≈100 kg of $^{82}$Se foils spread among 20 detector modules. The proposed geometry is planar. The energy resolution will be improved from 12 % to 7 % FWHM to improve the signal detection efficiency from 8% to 40% and reduce the 0νDBD contribution. The proposed detector dimensions will require a larger hall than is currently unavailable at Frejus and an expansion of the facility is therefore required and actively pursued. A demonstrator (single module) is funded and will completed in 2011 with a test run in the current NEMO3 site. New developments have been recently proposed concerning the possibility to disperse 0νDBD active isotopes in large masses of low-activity scintillators. SNO+ [14] is pursuing the goal of studying $^{150}$Nd with 50 to 500 kg of isotopically enriched Nd depending on the results of the currently ongoing R&D program. A similar approach is proposed by KamLAND [15], but for $^{136}$Xe. Their program should start in 2011 (phase-I) with 200-400 kg of isotope and continue in 2013 with 1 ton of Xe enriched to 90 % in $^{136}$Xe. A preliminary estimate of the 5 y sensitivity for phase I amounts to ≈$10^{26}$ y.

## 5. Conclusion

Recent discoveries on neutrino oscillation focused the interest of the Particle Physic community on 0νDBD search, as the only tool that can confirm the Majorana nature of neutrino. Present generation experiment will start exploring the $<m_\nu>$ IH region within few years. Nevertheless a clear strategy for a sub-meV sensitive experiment is still not present. Moreover pushing sensitivities to the DH mass region will require not only a zero background high sensitivity experiment but also a total mass of 20 - 100 tons. An international effort is however supporting a phased 0νDBD 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 region of interest. The claimed HM-KK evidence for a 0νDBD signal could be soon verified by the forthcoming next generation experiments. In conclusion, present and near future experiments will add a complementary set of measurement that will surely improve our knowledge of the neutrino properties. In particular, if neutrinos are Majorana fermions, next generation experiments will be able to solve the problem of the neutrino mass hierarchies.

REFERENCES


1. *Amsler C. et al. //* Physics Letters. - 2008. - Vol. B 667 - P. 1.
2. *Klapdor-Kleingrothaus H.V., Krivosheina I.V.* // Mod. Phys. Let. - 2006. - Vol. 21 - P. 1547 - 1566.
3. *Goeppert-Mayer M.* // Phys. Rev. - 1935. - Vol. 48 - P. 512.
4. *Avignone III F.T., Elliott S.R., Engel J.* // Rev. Mod. Phys. - 2008. -Vol. 80. - P. 2013.
5. *Furry W.H.* // Phys. Rev. - 1939. - Vol. 56. - P. 1184.
6. *Barea J., Iachello F.* // Phys. Rev. - 2009. - Vol. C 79. - P. 044301.
7. *Aalseth C.E. et al*. // Phys. Rev. - 2002. - Vol. D 65. - P. 092007.
8. *Lang K.* (*NEMO3 coll.*) // Proc. of the WIN09 Conf. (Perugia, Sept. 2009, Italy).
9. *Arnaboldi C. et al.* (*CUORICINO coll.*) // Phys. Rev. - 2008. - Vol. C 78. - P. 035502.
10. *Arnaboldi C. et al.* (*CUORE coll.*) // Nucl. Instr. Meth. - 2004. - Vol. A 518. - P. 775 - 798.
11. *Giuliani A.* (*Lucifer coll.*) // Proc. of Beyond 2010 Conf. (Cape Town, Febr. 2010).
12. *Dolinski M.J.* (*EXO coll.*) // Proc. of CIPANP 2009 Conf. (San Diego, May 2009).
13. *Kauer M.* (*SuperNEMO coll.*) // J. Phys.: Conf. Series. - 2009. - Vol. 160. - P. 012031.
14. *Zuber K.* (*SNO + coll.*) // AIP Conf. Proc. - 2007. - Vol. 942. - P. 101 - 104.
15. *Terashima A. et al.* // J. of Phys.: Conf. Series. - 2008. -Vol. 120. - P. 052029.
16. *Bettini A.* // Nucl. Phys. - 2007. - Vol. B 168. - P. 67 - 69.