Recent advances in neutrinoless double beta decay search

Lino Miramonti†
Physics Department of Milano University
&
National Institute of Nuclear Physics (INFN) of Milano
Via Celoria 16, 20133 Milano (Italy)

Franco Reseghetti‡
Italian National Agency for New Technologies, Energy and the Environment (ENEA)
Loc. S.Teresa, 19036 Pozzuolo di Lerici (Italy)

Abstract. Even after the discovery of neutrino flavour oscillations, based on data from atmospheric, solar, reactor, and accelerator experiments, many characteristics of the neutrino remain unknown. Only the neutrino square-mass differences and the mixing angle values have been estimated, while the value of each mass eigenstate still hasn’t. Its nature (massive Majorana or Dirac particle) is still escaping. Neutrinoless double beta decay ($0\nu$-DBD) experimental discovery could be the ultimate answer to some delicate questions of elementary particle and nuclear physics. The Majorana description of neutrinos allows the $0\nu$-DBD process, and consequently either a mass value could be measured or the existence of physics beyond the standard should be confirmed without any doubt. As expected, the $0\nu$-DBD measurement is a very difficult field of application for experimentalists. In this paper, after a short summary of the latest results in neutrino physics, the experimental status, the R&D projects, and perspectives in $0\nu$-DBD sector are reviewed.

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† e-mail: miramonti@mi.infn.it
‡ e-mail: reseghetti@santateresa.enea.it
1. Introduction

Recent experimental results and analyses from atmospheric, solar, accelerator and reactor neutrino physics, [1] [2] [3] [4] [5] [6], indicate that neutrinos change their flavour, and, consequently, do have a mass. Unfortunately, in the oscillation experiments only the square-mass differences between pairs of flavours and the mixing angle can be estimated, while the magnitude of the masses still remains unknown.

A fundamental question arises: Is the neutrino coincident with its own anti-particle? If the answer is positive, a neutrino is a Majorana massive particle, if not, a Dirac massive fermion.

This is a crucial point. If neutrinos and anti-neutrinos are identical, the balance between particles and anti-particles in Early Universe could have been modified, leading to the asymmetry between matter and anti-matter. Consequently, the Majorana nature of neutrinos is linked to the observed baryon asymmetry.

A possible answer is given by the $0\nu$-DBD process, which violates the lepton number by two units, and it is forbidden if neutrino differs from anti-neutrino. Such a reaction is a unique tool to measure the Majorana neutrino phases, and to determine the absolute neutrino mass scale. The double beta decay (DBD) is a very rare nuclear transition firstly described in the 30’s by Maria Goeppert-Mayer, [7], who estimated the half-life of the process to be very long. Few years later, Majorana proposed a fermion two-component theory alternative to the Dirac description, [8]. Racah also described the possibility of the transformation of two neutrons into two protons, with the emission of 2 electrons, but without neutrinos, [9]. Then, Furry quoted shorter half-life for $0\nu$-DBD reactions, [10].

We remind that such two-component fermions are called Majorana particles, whereas Dirac fermions are four-component particles.

DBD is a second order weak semileptonic spontaneous nuclear transition in which nuclear electric charge changes by two units, whereas the mass number remains unchanged. Sometimes, two nucleons (protons or neutrons) simultaneously emit a lepton pair each, that has been observed in a number of experiments. Such a process occurs only if the parent decaying nucleus is less bound than the final one, the intermediate nucleus being less bound than both these nuclei.

Different cases are allowed, with or without the emission of neutrinos, and of other particles. Many nuclei undergo these processes: the paring force makes the even-even nuclei, which have an even number both of protons and neutrons, more stable than odd-odd nuclei, with broken pairs. The usual beta decay transition from an even-even parent nucleus to a neighbouring odd-odd nucleus $((A,Z)\rightarrow(A, Z+1))$ is energetically forbidden, whereas the DBD transition to the daughter nucleus $(A, Z+2)$ is allowed.

DBD process naturally occurs for a few tenths of even-even nuclei, mainly from initial ground to final ground states, see [11] [12] [13]. In table 1 a list of possible interesting reactions having a high Q value is shown. In the case of $^{48}$Ca and $^{96}$Zr, the standard beta decay is energetically allowed, but strongly suppressed because of the
Table 1. Compilation, ordered by following the atomic mass number, of DBD candidate nuclei with $Q_{\beta\beta} > 1.7$ MeV. In last column, $r$ shows the isotopic abundance fraction in percent.

| Isotope | $Q_{\beta\beta}$ (keV) | $r$ (%) |
|---------|------------------------|---------|
| $^{48}$Ca | 4272 | 0.187 |
| $^{76}$Ge | 2039 | 7.61 |
| $^{82}$Se | 2995 | 8.73 |
| $^{96}$Zr | 3350 | 2.80 |
| $^{100}$Mo | 3034 | 9.63 |
| $^{110}$Pd | 2000 | 11.72 |
| $^{116}$Cd | 2805 | 7.49 |
| $^{124}$Sn | 2287 | 5.79 |
| $^{130}$Te | 2529 | 34.08 |
| $^{136}$Xe | 2468 | 8.87 |
| $^{148}$Nd | 1929 | 5.7 |
| $^{150}$Nd | 3367 | 5.6 |
| $^{160}$Gd | 1730 | 22.86 |

large difference in angular momentum $0^+ \rightarrow 6^+$. It has to be pointed out that the second-order process is allowed if $Q$ is positive, but, if a single beta decay parent nucleus is unstable, it is practically impossible to distinguish the DBD from the usual, and most intensive, beta decay, i.e. the background.

We underline that in the Standard Model of Electroweak Interaction and Particles, a massless Dirac neutrino is introduced, and the $2\nu$-DBD reaction is allowed. Such a theory was very successful in all tested applications, and represented the most economical theory explaining weak and electromagnetic interactions, but experimental results, mainly from the neutrino sector, have shown its inadequacy. Moreover, it gives no answer to a lot of fundamental questions. Among them, we mention the "anomalous" difference between neutrino and the corresponding charged lepton mass, and the neutrino nature (Dirac or a Majorana particle).

The deficit of the solar neutrino flux and its complicated energy dependence is evident in all the known experiments. Atmospheric neutrinos show an anomalous ratio and an unexpected angular distribution between electronic and muonic components. Finally, the disappearance of neutrinos in a Japanese accelerator long baseline experiment, and the deficit in the measured anti-neutrino flux emitted by Japanese reactors, definitively confirm that neutrino flavour oscillations do occur, and, consequently, neutrinos do have a non-zero mass.

Therefore, DBD physics is still a fundamental field of application for both particle and nuclear physicists, as pointed out many years ago in [14]. Its experimental detection requires good technical advances, mainly looking for the background suppression. It also offers several constraints to the calculations of nuclear properties.
Taking into account the negligible decay rates, and problems with the evaluation of nuclear matrix elements, measured lifetimes agrees satisfactorily with theoretical values, and the process appears to be sufficiently understood.

We remember also that many good reviews, and dedicated papers on DBD processes have been prepared, see for instance [15], [16] and reference therein.

We also mention the Neutrinoless Double Beta Decay section of the NEUTRINO UNBOUND web page \[http://www.nu.infn.it/\], for a complete list of papers and links concerning the $0\nu$-DBD physics.

2. Neutrino and Double Beta Decay

2.1. Neutrino mass and flavour oscillations

Massive fermions are described by the four-component Dirac equation, in which left and right chirality eigenstates are coupled. However, in the Standard Model of particles and interactions only left-handed neutrinos have interactions.

The neutrino Lagrangian has a Lorentz invariant mass term which includes three components. The first one (Dirac mass term) conserves the lepton quantum number and requires two chirality eigenstates: left and right. The remaining ones (Majorana mass terms) violate the lepton number conservation, and each exists independently of the other element. Usually, two non-degenerate mass eigenvalues for each flavour are the result of the diagonalization of the more general Lagrangian.

The most relevant case occurs when only the left mass $N \times N$ matrix is different from 0, where $N$ is the number of neutrino flavours. Then, the unitary $U$ matrix contains $N^2$ real parameters, $N(N-1)/2$ angles and $N(N+1)/2$ phases, whereas $N$ terms represent unphysical phases. In reactions where the flavour lepton number changes, but not the total lepton number, such as in oscillation experiments, all mixing angles and $(N-1)(N-2)/2$ phases, which describe CP violation and the related possible oscillation probability differences between neutrinos and anti-neutrinos, can be computed. $(N-1)$ phases can be calculated from processes like $0\nu$-DBD reactions, in which the total lepton number changes, but they have significance only for Majorana neutrinos. Practically, three CP violating phases appear in $U_{li}$ for Majorana particles [17].

We assume that the flavour fields $\nu_{lL}$ ($l = e, \mu, \tau$) are mixtures of the fields of three active neutrinos with definite masses, without the contribution of sterile neutrinos.

$$\nu_{lL} = \sum_{i=1}^{3} U_{li} \nu_{iL}, \quad (1)$$

where $\nu_i$ is the field of neutrino (Dirac or Majorana), and $U_{li}$ is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) $3 \times 3$ unitary left-handed lepton mixing matrix, which correlates the physical weak eigenstates ($l = e, \mu, \tau$) to the mass eigenstates $m_i$ ($i = 1,2,3$).
The $U_{li}$ matrix takes the following form in the standard representation:

$$U_{li} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}$$

(2)

Therefore, the value of $\langle m_\nu \rangle$ depends on the value of the individual neutrino mass eigenstates $m_i$, the mixing matrix elements $U_{ei}$ of the first row, and the Majorana phases $\alpha_i$ (where $\alpha_{ij} = \alpha_i - \alpha_j$). If three light massive Majorana neutrinos exist, the weak eigenstates $\nu_e$, $\nu_\mu$, and $\nu_\tau$ are a superposition of the mass eigenstates and the effective neutrino mass is:

$$\langle m_\nu \rangle^2 = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2 = \left| \sum_{i=1}^{3} |U_{ei}|^2 e^{i\alpha_i} m_i \right|^2$$

(3)

where two CP violating Majorana phases $\alpha_i$, which can be cancelled in the sum operation, are also included, and the neutrino mass element $|\langle m_{ee}^\nu \rangle|$ is

$$|\langle m_{ee}^\nu \rangle| = \left| m_1 |U_{e1}|^2 e^{i\alpha_1} + m_2 |U_{e2}|^2 e^{i\alpha_2} + m_3 |U_{e3}|^2 \right|$$

(4)

Left-handed V-A weak currents and Majorana massive neutrinos are needed to describe the interactions occurring in oscillation experiments. Newest results provide data which strongly constrains the mixing matrix elements and the differences in the square of masses eigenvalues, $\Delta m^2_{ij} \equiv m_j^2 - m_i^2$. Terms with label $\{1,2\}$ describe solar mixing sector, whereas label $\{2,3\}$ is concerning atmospheric mixing.

By now, we have clear evidence about neutrino oscillation and flavour mixing from the study of neutrino produced from different sources [18].

2.2. Experimental results

At the begin of summer 2004, several analyses and new measurements have been presented by different collaborations. The available results are shortly resumed.

2.2.1. Atmospheric neutrino experiments

Latest analyses on SuperKamiokande atmospheric neutrino dataset, [2] [3], which are based on 1489 live-days exposure and on enlarged fiducial volume for fully contained events (from 22500 to 26400 ton), confirm the deficit in the muon neutrino flux with a strong zenithal dependence. The best explanation of such measurements is given in terms of a flavour transition $\nu_\mu \rightarrow \nu_\tau$, with a squared mass difference $\Delta m^2_{atm}$ in the range

$$1.9 \cdot 10^{-3} < \Delta m^2_{atm} < 3.0 \cdot 10^{-3} (eV)^2$$

(5)

at 90% C.L., and a best fit value $\Delta m^2_{atm} \simeq 2.4 \cdot 10^{-3} (eV)^2$. The associated atmospheric mixing angle $\sin^2 2\vartheta_{atm}$ is $\simeq 1.0$ (i.e. maximal mixing angle), with the 90% C.L. lower bound

$$\sin^2 2\vartheta_{atm} > 0.90$$

(6)
2.2.2. Solar neutrino experiments The SuperKamiokande collaboration has recently presented an improved analysis on measurements before the incident (SK-I), and preliminary results with the new detector setup (SK-II), at a higher energy threshold, \[6\]. The obtained flux, which is \(\sim 45\%\) of the predicted one, strengthens the previous values.

The whole interaction rate for Gallium experiments, \(68.10 \pm 3.75\) SNU, \[19\], is practically constant over a decade, even if data since 1997 could indicate a slightly reduced solar neutrino flux in latest years. SNO results indicate a great suppression of the flux for charged current and elastic scattering events, and an indisturbed flux for neutral currents interactions, \[1\]. Consequently, the conversion from \(\nu_e\) to \(\nu_\mu/\nu_\tau\) arises as a natural explanation of the deficit and of the energy spectra, with

\[
\Delta m^2_{\text{Sun}} \sim 7.0 \cdot 10^{-5} (eV)^2 \quad \tan^2 \theta_{\text{Sun}} \sim 0.42 \quad (7)
\]

2.2.3. Reactor neutrino experiments In June 2004, KamLAND collaboration has published the analysis of data collected between March 2002 and January 2004, with a slightly enlarged fiducial volume and improved detection setup, \[4, 20\]. The expected anti-neutrino flux in absence of oscillation phenomena is \(365.2 \pm 23.7\) events, whereas 258 events have been detected. This result is well explained if a flavour oscillation occurs; the best fit is obtained with

\[
\Delta m^2_{12} = 8.3 \cdot 10^{-5} (eV)^2 \quad \tan^2 \theta_{12} = 0.41 \quad (8)
\]

The decay solution and the decoherence description are excluded at 95\% and 94\%, respectively.

2.2.4. Long baseline accelerator neutrino experiments New results have been released by K2K collaboration, \[5\], after the installation of SCIBAR apparatus: 108 events have been detected, whereas the expected number of interactions is 150.9. As in previous dataset, the deficit is mainly due to \(\mu\)-like events (57 detected interactions instead 84.8 expected events). The best-fit solution in physical region is obtained with the following values:

\[
\Delta m^2_{23} = 2.73 \cdot 10^{-3} (eV)^2 \quad \sin^2 2\theta_{23} = 1.00 \quad (9)
\]

The neutrino oscillation is confirmed at 3.9 \(\sigma\), whereas the significance of \(\nu_\mu\) disappearance is at a level of 2.9 \(\sigma\), and the energy spectrum distortion is at a level of 2.5 \(\sigma\).

Before latest experimental results from KamLAND, the mass values around \(\sim 1.5 \cdot 10^{-4}(eV)^2\) (the high Large Mixing Angle solution) was not completely discarded, see for instance \[21, 22, 23\]. At the present moment, this mass solution and the maximal mixing are strongly disfavoured.
Table 2. Summary of the best-fit values for atmospheric, long baseline accelerator, solar neutrino and long baseline anti-neutrino reactor experiments at the begin of Summer 2004.

| Parameter | Value |
|-----------|-------|
| $\Delta m_{23}^2$ | $2.4 \cdot 10^{-3} (eV)^2$ |
| $\Delta m_{12}^2$ | $8.2 \pm 0.3 \cdot 10^{-5} (eV)^2$ |
| $\sin^2 2\theta_{23}$ | $> 0.90$ for $\theta_{13}=0$ |
| $\sin^2 \theta_{13}$ | $< 0.015$ |
| $\tan^2 \theta_{12}$ | $0.39^{+0.05}_{-0.04}$ for $\theta_{13}=0$ |

2.3. Mass classification schemes

The previously quoted values can be accommodated in the framework of three neutrino mixing, which describes the three flavour neutrinos ($\nu_e$, $\nu_\mu$ and $\nu_\tau$) as unitary linear combinations of the three massive neutrinos ($\nu_1$, $\nu_2$ and $\nu_3$) having masses $m_1$, $m_2$, and $m_3$, respectively. The best-fit oscillation parameters are summarised in Table 2.

The $\Delta m^2$ values deduced by the experiments give the following constraint:

$$\Delta m_{12}^2 \ll \Delta m_{23}^2 \quad (10)$$

The experimental measurements are compatible with three mass schemes:

(i) Normal hierarchy: $m_1 < m_2 < m_3$

$$\Delta m_{12}^2 \simeq \Delta m_{\text{Sun}}^2 \simeq m_2^2 \quad \Delta m_{23}^2 \simeq \Delta m_{\text{atm}}^2 \simeq m_3^2 \quad (11)$$

(ii) Inverted hierarchy: $m_3 < m_1 < m_2$

$$\Delta m_{12}^2 \simeq \Delta m_{\text{Sun}}^2 \quad \Delta m_{23}^2 \simeq -\Delta m_{\text{atm}}^2 \quad \Delta m_{13}^2 \simeq m_1^2 \quad (12)$$

(iii) Degenerate case: the values of $\Delta m_{ij}^2$ are small when compared to each mass values. Usually, $m_1$ is assumed to be the smaller mass, and the hierarchies are indistinguishable.

$$\Delta m_{ij}^2 \ll m_1^2 \quad (13)$$

In figure ["normal" and "inverted" hierarchies are shown.

At high values of neutrino mass (but below 1 eV), the mass spectrum is practically degenerate. On the contrary, below $\sim 0.05$ eV the degenerate interval splits into two branches: $m_1$ is the lightest mass eigenstate in the normal hierarchy, whereas the inverted hierarchy occurs if $m_3$ is the lightest one.

In the normal scheme, large cancellations are possible between $\nu_1$, $\nu_2$, and $\nu_3$ mass contributions independently on the CP conservation, see [18]; thus, the $|\langle m \rangle|$ value can be arbitrarily small. Then, the smallest $\Delta m^2$ is realized by the two lightest neutrinos, and a natural neutrino mass hierarchy can be realized if $m_1 < m_2$.

On the contrary, in the inverted scheme, the cancellations are limited, because $\nu_1$ and $\nu_2$ (for $\nu_1$ and $\nu_2$ the electron neutrino has large mixing) are almost degenerate, and much heavier than $\nu_3$, independently on its value. The smallest $\Delta m^2$ is obtained by the two heaviest neutrinos.
The elements of the PMNS mixing matrix can be related to the effective mixing angles deduced from experiments. Usually, an allowed range for the mixing matrix elements is obtained. Owing of $U_{e3}$ smallness ($\sim 5 \cdot 10^{-2}$), mainly due to CHOOZ negative results, solar and atmospheric neutrino oscillations are practically decoupled,\cite{24}.

A complete cancellation between the contributions of $\nu_1$ and $\nu_2$ is excluded because the solar mixing angle is less than maximal. In the inverted hierarchy, this features puts a lower bound on the effective neutrino mass $|\langle m \rangle| \approx 0.001$ eV. We emphasize that if the mass is smaller than this value, either neutrinos have a mass hierarchy or they are Dirac particles. Unfortunately, new $0\nu$-DBD experiments planned for the next decade will have a sensitivity not better than 0.01 eV, therefore even new detectors cannot analyse this mass region.

Thanks to the oscillation experiment results, limits on neutrino mass are available:

- **$m_1 \ll m_2 \ll m_3$**
  
  In the normal hierarchy case, we obtain:
  
  $m_1 \ll \sqrt{\Delta m_{\text{Sun}}^2}$; $m_2 \simeq \sqrt{m_1^2 + \Delta m_{\text{Sun}}^2}$; $m_3 \simeq \sqrt{m_1^2 + \Delta m_{\text{atm}}^2}$ \hspace{2cm} (14)

  The presently deduced upper limit to the effective neutrino mass is of $\sim 0.0046$ eV.

- **$m_3 \ll m_1 < m_2$**
  
  In the inverted hierarchy case:
  
  $m_3 \ll \sqrt{\Delta m_{\text{atm}}^2}$; $m_1 \simeq \sqrt{m_3^2 + \Delta m_{\text{atm}}^2}$; $m_2 \simeq \sqrt{m_3^2 + \Delta m_{\text{atm}}^2}$ \hspace{2cm} (15)

  If the $0\nu$-DBD half-life will be precisely measured, precious information about Majorana CP phase difference will be available.

- **$m_1 \simeq m_2 \simeq m_3$**
  
  If the effective Majorana neutrino mass is large ($\gg 0.045$ eV $\sim \sqrt{\Delta m_{\text{atm}}^2}$), the neutrino mass spectrum is almost degenerate. A description in term of $m_1$ is
allowed, \(0.4 m_1 \leq |\langle m_\nu \rangle| \leq m_1\). If \(m_1\) will be determined from beta decay experiments or from cosmological measurements, accurate value of \(0\nu\)-DBD half-life could offer strong constraints on Majorana CP phase differences.

The present best limit on neutrino mass from tritium beta decay experiments is of 2.2 eV, whereas the best value from \(0\nu\)-DBD reactions has been obtained by the Heidelberg-Moscow and IGEX \(^{76}\)Ge experiments. The upper limit ranges from 0.3 to 1.3 eV, depending on the nuclear matrix element value.

In the last two years, new cosmological measurements have put stronger constraints on neutrino mass. Different upper limits on the sum of three neutrino masses, at 95% of C.L., have been computed within the range 0.69 eV, [25], and 1.7 eV, [26], depending on the selected values of associated parameters. This implies an upper limit to the neutrino mass, which should be not greater than 0.6 eV.

Data from the PLANCK satellite and the SDSS experiment could improve the present sensitivity down to 0.04 eV, but all these values are strongly analysis dependent. Taking into account the upper cosmological bound, the absolute scale of neutrino mass lies between 0.04 eV and 0.4 eV. Unfortunately, from a theoretical point of view, this is a wide range of mass, in fact one order of magnitude mass interval allows contradictory conclusions, [27].

2.4. Decay processes

Double beta decays are reactions in which the parent nuclei emit 2 electrons (or positrons) and other light particles. At the end of such processes, the decaying nuclei vary their electric charge by two units, but their atomic mass remains unchanged. Such decays can be observed only if similar processes are absent, i.e. if the intermediate nucleus has a mass larger than that of the parent one, or the usual beta decay is strongly forbidden.

Both neutrons and protons can originate DBD reactions, but, in this paper, only the emission of 2 electrons is considered, this implies that neutrons transform into protons.

There are different decaying ways, with or without neutrinos and/or other particle emission. In the first one, 2 neutrons (which are bounded in a nucleus) transform into 2 protons, and 2 electrons and 2 neutrinos are emitted:

\[
(Z, A) \rightarrow (Z + 2, A) + e^-_1 + e^-_2 + \bar{\nu}_{e_1} + \bar{\nu}_{e_2}
\]

This reaction, which is labelled as \(2\nu\)-DBD, does not vary the total lepton number \(L\), and is fully consistent with the Standard Model of electroweak interactions (SM). The \(2\nu\)-DBD half-life is proportional to the Fermi coupling constant, more precisely \(\propto G_F^{-4}\), and, consequently, it is a slow process, [11], [28].

An important theorem valid for any gauge model with spontaneous broken symmetry at weak scale states that a \(0\nu\)-DBD process amplitude different from the null value is equivalent to a non-zero Majorana neutrino mass. The same result has been extended to the SUSY-versions by [29]. The simplest mechanism allowing \(0\nu\)-DBD reactions is based on left-handed V-A weak currents with the exchange of light
massive Majorana neutrinos, see [30]; in such a reaction two electrons are emitted without neutrinos:

\[(Z, A) \rightarrow (Z + 2, A) + e_1^- + e_2^- \]  \hspace{1cm} (17)

This decay was proposed by Racah in 1937, and Furry in 1939, and foresees the violation by two units of the total lepton number. It can occur if and only if neutrino is a Majorana particle (i.e. the particle is coincident with its own anti-particle). Such a neutrino can be emitted by the first neutron decay; then, it reverses its helicity from right to left handed, due to its mass and/or a right handed current mixing in weak interactions. Practically, the neutrino emitted by the first neutron is reabsorbed by the second neutron in the reaction

\[n + \nu_e \rightarrow p^+ + e^- \]  \hspace{1cm} (18)

In a 0ν-DBD process, only real electrons are created, while two nucleons exchange a virtual neutrino. Thus, the electron would carry the decay energy, this is an evident signature of the reaction, and makes up for the low probability of this process. The main problem is whether virtual neutrino can be exchanged between two identical weak vertices. It is equivalent to the question of whether a real neutrino can be captured by protons or neutrons, which has been excluded by Davis’s experiment in 50’s, and is reflected in the conservation of lepton number.

Other processes, which violates the total lepton number, may produce 0ν-DBD reactions. Among them, we mention leptoquarks, supersymmetric particles, and heavy Majorana neutrinos, see [28], [29], [31], [32]. The possibility of connections with the equivalence principle and the dark energy sector has also been analysed. The development of grand unified theories (GUTs), such as in the simplest case of \(SO(10)\), [33], left-right symmetric models, or in the minimal supersymmetric standard model (MSSM), extended the electroweak \(SU(2)_L \otimes U(1)\) theories and greatly enhanced the interest in neutrino sector, offering several mechanisms to allow the 0ν-DBD process.

A third decay mode is the emission of two electrons with Majorons (\(\chi\)), which are light neutral Nambu-Goldstone bosons, due to the spontaneous breaking of a global symmetry associated with the lepton number conservation. Such hypothetical neutral pseudoscalar massless particles should be coupled with the neutrino, and emitted in the 0ν-DBD process, [34], [35]:

\[(Z, A) \rightarrow (Z + 2, A) + e_1^- + e_2^- + \chi(+\chi) \]  \hspace{1cm} (19)

Some models proposed either the emission of two Majorons (within super-symmetric theories), and a vector Majoron (a longitudinal component of a massive gauge boson). It has been pointed out the importance of the Majoron in the evolution of the early Universe and of the stars.

In short, 0ν-DBD process can be mediated by the exchange of Majorana neutrinos, light or heavy, but massive, or less conventional particles (see figure 2). Its amplitude, which is strictly related to the mass and coupling constants of such particles, is used to check and constrain the adopted parameters.
2.5. Half-life of DBD processes

The value of the half-life and the energy value of a physical process give an indication of the difficulties experimentalists have to face in order to measure such reaction.

In the case of $2\nu$-DBD process, the inverse half-life $T_{1/2}^{2\nu}$ is free of unknown parameters, and depends on exactly calculated integrated phase space factor $G^{2\nu}$, and $2\nu$-DBD nuclear matrix element, [36].

$$\left( T_{1/2}^{2\nu} \right)^{-1} = G^{2\nu} \cdot \left| M_{GT}^{2\nu} \right|^2$$  \hspace{1cm} (20)

Because of the large energy release, the most favoured processes are the transitions from the ground state $0^+$ of the parent nuclei to the ground state $0^+$ of the final nuclei.

The $2\nu$-DBD process has been measured for several nuclei, and the obtained half-lives (which are summarised in Table 3) vary from $10^{19}$ up to $10^{24}$ y, also representing the weakest measured physical process. We remind that in 1987 the experimental discovery of such a process in $^{82}$Se, based on non-geo-chemical measurements, was firstly announced, see [37] and reference therein.

The nuclear mass element calculation is a very critical point, due to the uncertainties in the description. Therefore, experimental measurements of $2\nu$-DBD half-lives can offer strong constraints to the value of related nuclear matrix elements, providing important tests of nuclear structure calculations [31].

The decay probability for the $0\nu$-DBD can be written, see [36] [31]:

$$\left( T_{1/2}^{0\nu} \right)^{-1} = C_{mm}^{0\nu} \left( \frac{m_\nu}{m_e} \right)^2 + C_{m\lambda}^{0\nu} \langle \lambda \rangle \left( \frac{m_\nu}{m_e} \right) +$$

$$+ C_{m\eta}^{0\nu} \langle \eta \rangle \left( \frac{m_\nu}{m_e} \right) + C_{\lambda\lambda}^{0\nu} \langle \lambda \rangle^2 + C_{m\eta}^{0\nu} \langle \eta \rangle^2 + C_{\lambda\eta}^{0\nu} \langle \lambda \rangle \langle \eta \rangle$$  \hspace{1cm} (21)
In the equation, \( \langle m_\nu \rangle \), see equation (3), is the effective neutrino mass, \( m_e \) is the electron mass, while \( \langle \lambda \rangle \) and \( \langle \eta \rangle \) represent the effective weak coupling constant of right-handed and the left-handed nucleonic current. For a definition of the \( C_{ij}^{0\nu} \) through the specific nuclear matrix elements, and phase-space factors of 0\( \nu \)-DBD, see for instance [36, 31].

If all \( C_{ij}^{0\nu} \) coefficients are known, all the nuclear matrix element values can be calculated; in this case, for a given value (or limit) of the 0\( \nu \)-DBD half-life, equation (21) represents an ellipsoid which restricts the allowed range of unknown parameters 0\( \nu \)-DBD: \( \langle m_\nu \rangle \), \( \langle \lambda \rangle \) and \( \langle \eta \rangle \) [11].

If right-handed contributions (i.e. \( \langle \lambda \rangle = 0 \) and \( \langle \eta \rangle = 0 \)) are not taken into account, the half-life of the \( 0^+ \rightarrow 0^+ \) transition can be expressed as for for 2\( \nu \)-DBD reaction, see equation (21)

\[
(T_{1/2}^{0\nu})^{-1} = C_{mm}^{0\nu} \cdot \left| M_{GT}^{0\nu} - \frac{g^2}{g_A^2} M_{F}^{0\nu} \right|^2 \cdot \langle m_\nu \rangle^2
\]

where \( m_\nu \) is the effective neutrino mass, whereas the \( G_{mm}^{0\nu} \) the phase-space integral. The nuclear mass elements \( M_{GT}^{0\nu} \) and \( M_{F}^{0\nu} \) form the nuclear structure parameter \( F_N \):

\[
F_N = G_{mm}^{0\nu} \cdot \left| M_{GT}^{0\nu} - \frac{g^2}{g_A^2} M_{F}^{0\nu} \right|^2
\]

In such a transition, an electron is emitted in each vertice of the diagram, and the amplitude of the 0\( \nu \)-DBD reaction contains a term \( U_{ei}^2 \), and is proportional to

\[
\langle m_\nu \rangle = \sum_i m_i U_{ei}^2
\]
where the sum includes only light massive neutrinos. As previously mentioned, the so
computed mass is the effective neutrino mass, which depends on the Majorana phases,
because of the term $U_{ei}^2$ instead of $|U_{ei}|^2$. In short, the $0\nu$-DBD rate is directly related to
the square of the effective Majorana mass $\langle m_\nu \rangle$, to a calculable phase space factor $G_{mm}^{0\nu}$,
and to the square of $a$, difficult to compute, nuclear matrix element.

If also Majorons are emitted, the corresponding $0\nu$-DBD rate can be obtained from
the previous equation substituting the effective neutrino mass $\langle m_\nu \rangle$ with the effective
Majoron neutrino coupling constant $\langle g_\chi \rangle$, and replacing the $G_{mm}^{0\nu}$ factor by the phase
space integral describing the massless Majoron and the two electrons in the final state
\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G_X^{0\nu} \cdot \left| M_{CT}^{0\nu} - \frac{g_\nu^2}{g_A^2} M_F^{0\nu} \right|^2 \cdot \langle g_\chi \rangle^2
\]

(25)

The phase space integrals $G_X^{2\nu}$, $G_{mm}^{0\nu}$ and $G_X^{0\nu}$ (where $G = G(Q_{\beta\beta} , Z)$) contain the
Fermi function $F(Q_{\beta\beta} , Z)$ which represent the Coulomb distortion of the wave function
of the emitted electrons. Tabulated values of $G^{2\nu}$, $G_{mm}^{0\nu}$ and $G_X^{0\nu}$ are collected in reviews,
see for example [36], [31].

DBD process toward final excited nuclear states offer several interesting
opportunities. The $2\nu$-DBD transition of $^{100}$Mo toward $0^+$ excited state of $^{100}$Ru was
successfully detected, see for instance [15], and other isotopes should present half-lives
values within actually detectable time intervals ($\sim 10^{21} - 10^{22}$ y). This suggests that
the suppression factor of such reactions is not as great as early supposed and should
allow the evaluation of additional properties of nuclear matrix elements.

Neutrinoless DBD reaction is one of the few important non-accelerator experiments
which may demonstrate the validity of GUTs well beyond the possibilities of present
and future accelerators.

For this reason, since 1948 several collaborations (at present, about 40 groups)
looked for this rare nuclear process. However, this great effort is till now without
results. We remind the first experimental limit to the $0\nu$-DBD process, at a level of
$> 3.0 \cdot 10^{15}$ y, based on Geiger detector technique.

Experimentally speaking, if electron energies are well measured, it should be easy to
identify such reactions among the different decay modes previously quoted. In fact, the
energy spectrum of emitted electrons is constrained by the phase space of out-coming
leptons, and strictly related to the decay process. Only indirect methods, as explained
in a later section, which allow only the total decay rate measurements, cannot identify
the decay reaction. The experimental half-life limits allow us to deduce the values for
several parameters; for example the effective neutrino mass parameters of right handed
currents and parameters of supersymmetric models.

In a $2\nu$-DBD process the available energy $Q_{\beta\beta}$ is shared between four particles
giving origin to a continuous spectrum. On the other hand, in $0\nu$-DBD reaction the
two electrons carry the full available energy, giving a sharp peak spectrum at the $Q_{\beta\beta}$
value. If Majorons are emitted in a DBD process, the two electron energy spectrum
is continuous, but its shape differs from that one of 2ν-DBD reaction. In fact, the maximum occurs at different energy value, (see figure 3). We remind that these particles do not interact with ordinary matter and escape detection. In case of transition toward final excited states, an evident experimental signature should be the comparison of one or two photons accompanying the two electrons of fixed total energy.

\textbf{Figure 3.} Schematic energy spectra for the emitted electrons calculated for different DBD processes. Each spectrum is normalized arbitrarily and independently on the others. In abscissa: the ratio $E/E_{\text{max}}$ between the sum electron kinetic energy divided by its maximum value.

\section*{2.6. The calculation of nuclear matrix elements}

In order to correctly interpret the 0ν-DBD experimental results, the mechanism of nuclear transitions must be understood. In other words, one has to evaluate the corresponding nuclear matrix elements with high reliability. A fine tuned nuclear matrix calculation, which is based on QCD, is a difficult task with nuclei having several nucleons:

- The parent nuclei have a complicated nuclear structure, and a many-body approximation in solving the calculation is naturally introduced.
- The complete set of states for the intermediate nucleus is a second order weak interaction process.
- There are many parameters involved in the calculations, like pairing interactions, nuclear deformations, mean field parameters and so on, and many values have to be fixed. Therefore, the introduced uncertainty is quite high.

The derived global uncertainty forbids any precise answer to the questions about neutrinos.

Two are the main approaches to calculate the DBD nuclear matrix elements: the shell model, see [64], and the neutron-proton Quasiparticle Random Phase Approximation (QRPA) model, see [28] [31].
The former was adapted to the DBD sector in the early 80’s by [14]. Improvements were realised mainly for $^{76}$Ge and $^{136}$Xe isotopes. It well describes only the reduced energy region of the lowest states for intermediate nuclei, and it does not include the effects from the Gamow-Teller resonance region.

The latter is the most used approach in recent years. It was firstly employed in the early 70’s, but many problems occurred in reproducing the decay rates for $2\nu$-DBD processes before the improvement done by [65]. Several upgrades on such model were developed starting from the 90’s, when DBD physics became more popular. Among them, we mention the Renormalized QRPA, [66] [67], the QRPA with proton-neutron pairing, [68], the full QRPA, [67] [69], the proton-neutron self consistent RQRPA, [70] [71], and the deformed QRPA, [72].

A comparison between theories and experiments for the $2\nu$-DBD process provides a measure of confidence in the calculated nuclear wave-functions employed for extracting the unknown parameters from $0\nu$-DBD life measurements. Usually, the $2\nu$-DBD rates have been estimated not to be fundamental constraints in calculations of $0\nu$-DBD nuclear matrix elements, because the intermediate nuclear states are quite different. Recently, it has been shown that, within the context of QRPA treatment, an accurate knowledge of $2\nu$-DBD rate allows the calculation of the nuclear matrix elements reproducing the experimental value for some isotopes, [73]. Therefore, the previously obtained variability is practically eliminated, and a strong improvement in the corresponding $0\nu$-DBD nuclear matrix elements seems to be possible.

We stress the great variability which occurs in present calculations. In the case of $^{76}$Ge isotope, the nuclear contribution to the decay rate obtained with 20 different approaches is dispersed over about two order of magnitude, see for instance [74] [75]. This is a consequence of the use in calculation of different methods, model spaces, fitted observables, and adjusted parameters. Therefore, results also concerning $0\nu$-DBD rates and neutrino mass have a large uncertainty.

3. Detection techniques

3.1. Preliminary aspects

In order to have an excellent experiment for DBD searches, which should take place very deep underground, a lot of properties should be verified:

- Large mass detector with compact dimension, looking for the detection of mass value lower than 0.1 eV.
- The possibility of event reconstruction, with a very good energy resolution.
- Good source radiopurity, reliable and easy to operate technology.
- Great natural abundance of the selected decaying isotope, which should have a large Q value, in order to reduce the background influence.
- Particle identification, mainly daughter nucleus, and reduced $2\nu$-DBD process interference.
Well understood nuclear calculations.

Practically, the ideal detector should have excellent sensitivity, in order to identify all the 0ν-DBD reactions, and almost null background. Clearly, this is a dream. Moreover, all previous requirements cannot be contemporaneously satisfied.

3.2. Measurement methods

Since the 50’s, the existence of DBD processes was established in pioneering experiments with geo-chemical measurements by searching for daughter nuclei in samples of materials enriched in parent isotopes. In 1949 the 2ν-DBD reaction was identified with $^{130}$Te, but only in 1967 another isotope ($^{82}$Se) confirmed such a transition. In fact, when the final isotopes are radioactive, also radiochemical measurements can be done. Only the total decay rate can be estimated in this way, but there is a great advantage due to the integration time over very long time. At the end of 80s, the 2ν-DBD process was successfully detected in $^{82}$Se by using a Time Projection Chamber, see [15] for details and references.

Up to now, there are two main experimental approaches:

- **Indirect** (or Inclusive) = These techniques, which had an important role in the past, measure the anomalous concentration of daughter nuclei in samples with a long accumulation time. They cannot distinguish between neutrino and neutrinoless processes, and have been used to give indirect evaluations of the 0ν-DBD and 2ν-DBD lifetimes. Among them, we mention geo-chemical and radiochemical methods.

- **Direct** (or Counter) = These are the presently most diffuse techniques, and are based on the direct observation of electrons emitted in the process. Unlike the inclusive method, and according to the different capabilities of the detector, energy, momentum, and topology of the decaying particles are recorded in this case. These detectors can identify the DBD reaction modes: 0ν-DBD process should be easily identified because of a mono-energetic line at the Q value. The better the detector energy resolution, the stronger the signal. Two technical approaches are possible:
  - Passive source = The source does not coincide with the detector and hence the electrons are originated in an external sample containing the decaying isotopes.
  - Active source = The DBD source also serves as the detector.

Different direct standard techniques are employed in DBD experiments, among them:

- **Scintillators**, such as Crystal scintillators and Stacks of plastic scintillators.
- **Gas counters**, such as Time Projection Chambers (TPC) and Multiwire Proportional Chambers (MWPC).
- **Solid state detectors**, such as High Purity Germanium semiconductors detectors (HPGe) and Silicon detector stacks.
- **Bolometers**
3.3. Background

In a $0\nu$-DBD experiment, the expected number of reactions strictly depends on the detector mass, and the measurement time. On the other hand, the greatest challenge for the experimentalists is the background recognition and elimination in the energy region around the expected $0\nu$-DBD emission line. The way out is to shield the detector and to eliminate internal radioactivity as much as possible. Therefore, apparatuses are always located deep underground, in experimental areas like Gran Sasso National Laboratory (LNGS) in Italy, Modane in France, Canfranc in Spain, Kamioka in Japan to shield from external components. In last years, some new shielded devices in Europe, in Asia, and in America, have opened up new opportunities.

There are many background components interfering with DBD processes detection. Among them, we mention:

- Primordial radionuclides, such as $^{238}\text{U}$, $^{232}\text{Th}$ and their daughters, produce dangerous emissions. Sometimes, their Q-values are as high as the DBD energy region, therefore, a superposition of spectra can occur. Further complications are created if a beta decay is promptly followed by an internal nuclear conversion which induces a reaction with two electrons. Radon and its daughters also contribute to the background, but their elimination is frequently obtained by purification in liquid nitrogen. Because of their low Q values, the $^3\text{H}$, $^{14}\text{C}$, and $^{40}\text{K}$ influence should be less dangerous, depending on the selected decaying isotope.

- Anthropogenic (man-made) radionuclides, such as $^{137}\text{Cs}$, $^{90}\text{Sr}$, $^{42}\text{Ar}$, and $^{239}\text{Pu}$, which were produced during atmospheric nuclear tests and/or accidents at nuclear plants.

- Cosmogenic isotopes, which have their decaying energy in the $0\nu$-DBD region. The intensity of different contributions is material dependent. It is hard to eliminate such components, even if a laboratory located deep underground greatly reduces their influence.

- Neutrons, due to the difficulty to identify such neutral particles: both neutron capture and fast neutron interaction. If the detector is located deep underground, these reactions are reduced, but a good knowledge of the neutron flux is required.

- Cosmic ray muon-induced events. A good solution is the deep underground location of the detector combined with a veto system to eliminate the prompt interaction via coincidence technique.

- $2\nu$-DBD reactions. Usually, the $2\nu$-DBD energy spectrum has low intensity in the $Q_{\beta\beta}$ region, but it can produce a dangerous background. A great energy resolution is needed in order to well identify true signals; sometimes, an asymmetric energy window, centred at Q value, is also selected.

In the last decades, several techniques aiming for a more complete evaluation of the background, and, consequently, its consistent reduction have been developed. Examples of this are: pulse shape analysis, topological information of the events, simultaneous
measurements of two signals such as heat and ionisation, or heat and scintillation and so on. Moreover, the strongly reduced width of the peak at the $Q_{\beta\beta}$ value can be masked by the $2\nu$-DBD tail for some DBD candidate nuclei. For this reason, a very good energy resolution is also necessary to detect the $0\nu$-DBD signal.

### 3.4. Detector performances

Experimentally speaking, a $0\nu$-DBD detector has to identify a known energy peak within a continuum spectrum, where energy lines due to different radioactive isotopes can be also present. Therefore, a wide knowledge of the background shape and intensity in surrounding energy region is needed in order to analyse the detected emissions.

Once the detector parameters are fixed, it is possible to calculate the expected number of background events, $N_B$, in an energy interval equal to the apparatus FWHM energy resolution, centred around the transition energy:

$$N_B = B \cdot \Delta E \cdot t \cdot m \quad (26)$$

In case of constant background level $B$, usually expressed in counts/(keV kg y), the background counts linearly scale with the measurements time $t$, the sensitive mass of the detector $m$, and the energy resolution $\Delta E$. Consequently, the half-life limit of $0\nu$-DBD can be written in the form:

$$T_{1/2}^{0\nu} \sim \frac{a}{W} \cdot \varepsilon \cdot \sqrt{\frac{m \cdot t}{B \cdot \Delta E}} \quad (27)$$

where $\varepsilon$ is the detection efficiency, $a$ the isotopic abundancy, and $W$ the molecular weight. About the detection efficiency, only direct methods allow a complete detection (100%).

As long as background is null, half-life grows as the sensitive mass and the measurement time, whereas in the case of background counts the dependence is on the square root of the same quantities. We consider two detectors with the same values of efficiencies, resolution, background, and running time, but with different masses and isotopic enrichments. The same sensitivity is obtained if the ratio between the masses is equal to the square of the inverted ratio between the isotopic abundancy. Usually, the mass under observation is isotopically enriched in the selected decaying nucleus, but this is a very expensive process. A relatively cheap technique is based on centrifugal isotope separation when the substance is in gaseous form, but it can be applied only to $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, and $^{136}$Xe isotopes. At present, only Russian plants allow this enrichment process. An alternative, but expensive method should use the atomic vapour laser isotope separation, even if the production program is up to now not planned. In this case, $^{48}$Ca, $^{100}$Mo, $^{116}$Cd and $^{150}$Nd enriched materials could be obtained at Livermore National Laboratory, USA. Moreover, a large mass production is possible only for some DBD candidate isotopes: e.g. $^{76}$Ge, $^{82}$Se, $^{116}$Cd, $^{130}$Te, and $^{136}$Xe.

A useful parameter is the detector sensitivity (or detector factor of merit), which is 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., [76]. In other words, the sensitivity is the lifetime corresponding to the minimum detectable signal above background fluctuations. It allows also the comparison of the performance among different experimental apparatuses. $F_{0\nu}$, which represents the inverse of the minimum rate detectable in a measurement time $t$, can be estimated, at 1\sigma level:

$$F_{0\nu} = T_{1/2}^{\text{Backg.}} = \ln 2 \cdot N_{\beta\beta} \cdot \varepsilon \cdot \frac{t}{\sqrt{N_B}} = \ln 2 \cdot (N_A k) \frac{a \varepsilon}{W} \sqrt{\frac{m t}{B \Delta E}}$$

(28)

where $N_{\beta\beta}$ is the number of observed $\beta\beta$ decaying nuclei, $N_A$ is the Avogadro number, and $k$ is the number of decaying nuclei per molecule. In this equation the role of each component is clearly emphasized. By equation (22), it is also possible to deduce the experimental sensitivity to the neutrino mass, $F_{(m_\nu)}$:

$$F_{(m_\nu)} = \sqrt{\frac{F_{0\nu}^{\text{Exp}} \cdot G_{0\nu mm} \cdot |NME|^2}{W N_A k a \varepsilon G_{0\nu mm}^2 |NME|^2 \left( \frac{B \Delta E}{m t} \right)^4}}$$

(29)

where NME are the nuclear matrix elements.

It is straightforward to conclude that very large sample masses (possibly enriched with DBD candidate nuclei) and very low background are needed to look for the identification of the effective neutrino mass. We point out that a sensitivity of $\sim 0.01$ eV is required in order to check inverse hierarchy.

Among the components of the background, the $2\nu$-DBD process can produce dangerous emissions. In fact, all the features of the two decay modes (with and without neutrinos) are equal: two electrons are emitted in one point inside the source, at the same time, in the same energy region and with the same angular distribution. No available techniques of discrimination can distinguish between $0\nu$-DBD and $2\nu$-DBD signals, and consequently, it is impossible the rejection of $2\nu$-DBD contributions. The latest, and more energetic, part of the $2\nu$-DBD spectrum overlaps the gaussian peak of the $0\nu$-DBD process. Therefore, a very important parameter is the energy resolution of the detector. The better this is, the smaller will be the undesirable $2\nu$-DBD contribution to the background in the analysed region (see figure 4).

As a further improvement, a very good estimate of the neutrino fluxes is required in experimental areas. We mention the solar neutrinos, namely the high energy component, the anti-neutrinos from nuclear power plants and from the Earth. This contribution produces a background which can significantly influence the instrumental sensitivity.

4. Experimental status

In this section we will briefly review some of the direct counting experiments, reporting only on DBD reactions to the ground state. The direct counting experiments using transitions toward excited states will not be detailed in the present paper, see [15] for a comprehensive analysis and the present experimental limits quoted in Table 3.
Figure 4. Energy spectra for the electrons emitted in $2\nu$-DBD (dotted line) and $0\nu$-DBD (full line) reactions, based on an energy resolution of 5%. On the X axis, the fraction between electron kinetic energies and the Q value is represented. The intensities have been normalized to different values for of $2\nu$-DBD and $0\nu$-DBD terms. In the upper inset, the contribution of $2\nu$-DBD reaction to the background of $0\nu$-DBD reaction has been enhanced, see [16].

4.1. Present Results

(i) $^{48}$Ca is the most favourable isotope among other potential $2\nu$-DBD nuclei because it has the largest Q value (4272 keV), hence the possibility of the occurrence is highest, and the expected background should be lower than in remaining candidate nuclei. A new CaF$_2$ scintillation detector system (ELEGANTS VI), which consists of 6.6 kg of CaF$_2$(Eu) crystals as sensitive mass, has been developed at the Oto Cosmo observatory, near Nara in Japan. The obtained energy spectrum after all cuts gives a lower limit for the half life of $T_{0\nu}^{1/2} > 1.4 \cdot 10^{22}$ y [77].

(ii) Two experiments have looked for the DBD of $^{76}$Ge nucleus.

- The Heidelberg-Moscow (HM) experiment, [40], which is located at LNGS, and employs a set of five large HPGe detectors enriched in $^{76}$Ge to 86-88%. The active total mass is $\sim$ 11 kg, which corresponds to 125.5 moles of $^{76}$Ge. Due to the passive, consisting of extremely low background materials, and active shields, the background is strongly reduced, $\simeq 0.2$ counts/(keV kg y) in the peak region. After the pulse shape discrimination analysis, its value is lowered to $0.113 \pm 0.007$ counts/(keV kg y) in the period 1995-2003, in the $0\nu$-DBD peak energy region, where the energy resolution is 3.9 keV. The data taking, which began in 1990 with a reduced setup, stopped in May 2003, for a total value of 71.7 kg·y. The half-life of the process has been determined on the basis of more than $10^5$ events. Some researchers of this collaboration have recently claimed the discovery of the $0\nu$-DBD process at a level of 4.2 $\sigma$, see [78] and references therein. We will briefly discuss this results in following sections.
Table 4. Results from NEMO-3 experiment for $2\nu$-DBD reactions, based on more than 140000 detected events [82]. The statistics and the systematic errors are also quoted. It has to be stressed the great variability in mass among different analysed isotopes. For a comparison with previous values see Table 3.

| Isotope | Mass (g) | $T^{1/2}_{1\nu}$ (y) |
|---------|---------|----------------------|
| $^{82}$Se | 932     | $(10.3 \pm 0.3 \pm 0.7) \cdot 10^{19}$ |
| $^{96}$Zr | 9.4     | $(2.0 \pm 0.3 \pm 0.2) \cdot 10^{19}$ |
| $^{100}$Mo | 6914    | $(7.68 \pm 0.02 \pm 0.54) \cdot 10^{18}$ |
| $^{116}$Cd | 405     | $(2.8 \pm 0.1 \pm 0.3) \cdot 10^{19}$ |
| $^{150}$Nd | 37      | $(9.7 \pm 0.7 \pm 1.0) \cdot 10^{18}$ |

The IGEX detector, which is homed at the Spanish laboratory of Canfranc, with a shield of about 4000 m.w.e., consists of three HPGe detectors enriched in $^{76}$Ge up to 88%, with a total active mass of at least 6 kg. After pulse shape discrimination analysis, the background rate is as great as in HM experiment in the energy interval between 2.0 and 2.5 MeV, while the energy resolution is 4 keV. Analysis on 8.9 kg $\cdot$ y ($^{76}$Ge) of data gives a lower bound of $T^{1\nu}_{1/2} > 1.57 \cdot 10^{25}$ y [79].

It has to be stressed that even if both the experiments gave an effective neutrino mass limit of 0.3 - 1.3 eV, IGEX detector has a background of 0.01 counts/(keV kg y), mainly internal(cosmogenic), whereas in old HM analyses the background was estimated as great as 0.06 counts/(keV kg y), mainly external.

(iii) Several collaborations have worked on $^{100}$Mo isotope, in particular NEMO, in France, and ELEGANT V, in Japan.

NEMO-3 experiment, which started its data taking in February 2003, is homed at Fréjus Underground Laboratory at a depth of $\sim 4800$ mwe. It is an improvement of NEMO-2 and analyses also the $2\nu$-DBD reactions of $^{82}$Se, $^{96}$Zr, $^{100}$Mo, and $^{116}$Cd. It is a cylindrical tracking detector (see Figure 5), divided into 20 equal sectors, and devoted to the search for $0\nu$-DBD processes with passive sources enriched up to 97% in $^{100}$Mo ($\sim 7$ kg). Thin (40-60 mg/cm$^2$) enriched foils of $\beta\beta$ emitters have been constructed from either metal films or powder bound by an organic glue to mylar strips [80] [81]. Its present FWHM at the $Q_{\beta\beta}$ values is of 90 keV. The expected sensitivity for the effective neutrino mass is on the order of 0.2 - 0.3 eV after 5 years of measurements.

At present, several interesting results available. In Table 4 $2\nu$-DBD main characteristics are shown, whereas $0\nu$-DBD values are quoted in Table 5.

The most stringent half-life limit is the one obtained by the ELEGANT V spectrometer in the Oto Cosmo Observatory by Osaka University. The detector consists of three drift chambers whose aim is to detect two $\beta$ trajectories, a sodium iodide crystal scintillator array to detect $\gamma$ rays, and plastic scintillators to measure the $\beta$ ray energies and arrival times [83]. The passive source
Figure 5. Schematic view of the NEMO-3 experimental setup where 1) indicates $\beta\beta$ isotope foils. The energy of electrons is measured by plastic scintillators 2) coupled to low activity PMTs 3). Moreover, 6180 drift cells operating in Geiger mode 4) allow the track resolution with a $1 \text{ cm}$ resolution. In addition, a solenoid surrounding the apparatus produces a $25 \text{ G}$ magnetic field parallel to the detector axis. The external passive shield (steel, water, wood and paraffin) have been removed.

consists of two foils enriched in $^{100}\text{Mo}$ up to $95\%$ whose thickness is $20 \text{ mg/cm}^2$ with a total mass of $\sim 170 \text{ g}$ inserted in a central drift chamber. The lower limit thus obtained is $T_{1/2}^{0\nu} > 5.5 \cdot 10^{22} \text{ y}$ [83].

(iv) Experiments with $^{116}\text{Cd}$ have been made by the Ukrainian Institute of Nuclear Research INR-Kiev (since 1998 in collaboration with the University of Florence) in the salt mine of Solotvina (Ukraine). The lower limit is $T_{1/2}^{0\nu} > 1.7 \cdot 10^{23} \text{ y}$.

(v) $^{130}\text{Te}$ isotope (and also $^{128}\text{Te}$) has been investigated by an Italian group based in Milan (INFN and Milan-Bicocca University), within the project MIBETA, by developing low temperature thermal detectors in the form of TeO$_2$ crystals (i.e. bolometers). This nuclide was primarily selected because of its natural isotopic abundance (34%), its high transition energy and a favourable nuclear factor of merit. Moreover, also geo-chemical techniques which use this isotope are available from long time.

The detector was homed at LNGS, and consists of an array of 20 TeO$_2$ crystals, with a total mass of $6.8 \text{ kg}$, which operate at a temperature of $\sim 12 \text{ mK}$; its resolution is $8 \text{ keV}$ in the $0\nu$-DBD region ($2528 \text{ keV}$). The background level in the same region is $0.33 \pm 0.11 \text{ counts/(keV kg y)}$. The lower limit is $T_{1/2}^{0\nu} > 2.1 \cdot 10^{23} \text{ y}$, corresponding to a range $0.9 - 2.1 \text{ eV}$ in $\langle m_\nu \rangle$ [76].

Since February 2003, a prototype called CUORICINO, which consists of an array of TeO$_2$ bolometers, for a total mass of $40.7 \text{ kg}$, is running at LNGS. The array is composed by 2 modules, 9 detectors each with $3 \times 3 \times 6 \text{ cm}^3$ crystals, and 11 modules, 4 detector each having $5 \times 5 \times 5 \text{ cm}^3$ crystals. Its FWHM at the $Q_{\beta\beta}$ value is $7 \text{ keV}$, [84] [85]. The background presently measured is $0.19 \pm 0.02 \text{ counts/(keV}$
kg y), and the live time is of 5.8 kg·y. No evidence of 0ν-DBD reactions has been detected during 2003 data taking. A half-life limit of $7.5 \cdot 10^{23}$ y at 90 % of C.L., which corresponds to a neutrino mass interval between 0.3 and 1.6 eV, has been deduced [86]. The estimated sensitivity after 3 years of data acquisition is $4 \cdot 10^{24}$ y, or, in mass, 0.2 - 0.5 eV. It will be an important test of CUORE project feasibility (see later) both for technical performance, and background level expectations [60].

(vi) The 0ν-DBD of $^{136}$Xe has been used for the Caltech-Neuchatel-PSI collaboration and the Italian group DAMA-LXe.

- The Caltech-Neuchatel-PSI detector consist of a time projection chamber with a total active volume of $\sim 180$ l, containing 3.3 kg of Xe gas ($\simeq 24$ moles) enriched in $^{136}$Xe to 62.5% at a pressure of 5 atm. The detector is located in the Gotthard underground laboratory in the Swiss Alps. At $Q_{2\beta} = 2481$ keV, the FWHM energy resolution is 6.6%. The background rejection is assured by the time projection chamber track reconstruction, and its value is $\sim 0.02$ counts/(keV kg y) in the $Q_{2\beta}$ region (within a FWHM interval energy). The obtained lower limit is $T_{0\nu}^{1/2} > 4.4 \cdot 10^{23}$ y [87].

- A better result has been obtained by the Roma group at LNGS, by using $\sim 6.5$ kg of high purity liquid Xenon scintillator has been filled by (Kr-free) Xe gas enriched in $^{136}$Xe (68.8%), and in $^{134}$Xe (17.1%). The statistics was 1.1 kg · y for $^{134}$Xe, and 4.5 kg · y for $^{136}$Xe. The lower limits obtained for half-life were $T_{0\nu}^{1/2} > 1.2 \cdot 10^{24}$ y for $^{136}$Xe and $T_{0\nu}^{1/2} > 5.8 \cdot 10^{22}$ y for $^{134}$Xe, at 90% of C.L. [61].

Half-life limits have been established experimentally for several nuclides; table 5 summarizes the measured values for 0ν-DBD and the effective neutrino mass ($m_\nu$) limits, or ranges, as deduced by the authors of different experiments. These results have already put the strongest constraint on the Majorana neutrino mass, which can vary between 0.3 eV and 5 eV, the right handed admixture in the weak interaction ($\eta \sim 10^{-7}$ and $\lambda \sim 10^{-5}$), the coupling constant between neutrino and Majoron ($g_M \sim 10^{-4}$), and the R-parity violating parameter in the MSSM ($\zeta \sim 10^{-4}$).

Direct measurements of 2ν-DBD gave positive results for several isotopes, the last ones being from $^{76}$Ge, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, and $^{150}$Nd. The values vary between $10^{19}$ and $10^{21}$ y, see Table 3.

The strongest limits on 0ν-DBD half-life, and, consequently, on neutrino mass, come from enriched $^{76}$Ge IGEX and HM experiments, which recently stopped their measurements after several years of data taking. Their results are consistent both in background level, $\sim 0.2$ counts/(keV kg y), before the pulse shape discrimination analysis, and in half-life limit, within the range 1.3 - 1.9 $\cdot 10^{25}$ y.

At the present moment, only NEMO-3 and CUORICINO detectors are running.
Table 5. Experimental 90% C.L. half-life limits for $0\nu$-DBD, except where noted. The effective neutrino mass upper limits and ranges have been deduced by the authors. The intermediate rows show the results concerning the claimed discovery of $0\nu$-DBD reaction: in upper row the $3\sigma$ interval is reported, whereas in the lower one the best fit values are quoted. In the final part, the latest published results.

| Isotope   | $T_{1/2}^{0\nu}$ (y) | References | $\langle m_\nu \rangle$ (eV) |
|-----------|----------------------|------------|-------------------------------|
| $^{48}$Ca | $> 1.4 \cdot 10^{22}$ | [77]       | $< 7.2 - 44.7$               |
| $^{76}$Ge | $> 1.9 \cdot 10^{25}$ | [40]       | $< 0.35$                     |
| $^{82}$Se | $> 2.7 \cdot 10^{22}$ | [43]       | $< 5.0$                      |
| $^{100}$Mo| $> 5.5 \cdot 10^{22}$ | [83]       | $< 2.1$                      |
| $^{116}$Cd| $> 1.7 \cdot 10^{23}$ | [89]       | $< 1.7$                      |
| $^{128}$Te| $> 7.7 \cdot 10^{24}$ | [58]       | $< 1.0 - 4.4$                |
| $^{130}$Te| $> 5.5 \cdot 10^{23}$ | [85]       | $< 0.37 - 1.9$               |
| $^{134}$Xe| $> 5.8 \cdot 10^{22}$ | [61]       | $< 17.0 - 27.0$              |
| $^{136}$Xe| $> 1.2 \cdot 10^{24}$ | [61]       | $< 0.8 - 2.4$                |
| $^{150}$Nd| $> 1.2 \cdot 10^{21}$ | [51]       | $< 3.0$                      |
| $^{76}$Ge | $(0.69 - 4.18) \cdot 10^{25}$ | [78] | $0.24 - 0.58$ |
| $^{76}$Ge | $1.19 \cdot 10^{25}$ | [78]       | $0.44$                       |
| $^{82}$Se | $> 1.4 \cdot 10^{23}$ | [82]       | $< 1.5 - 3.1$                |
| $^{100}$Mo| $> 3.1 \cdot 10^{23}$ | [82]       | $< 0.8 - 1.2$                |
| $^{130}$Te| $> 7.5 \cdot 10^{23}$ | [86]       | $< 0.3 - 1.6$                |

5. Next generation of DBD experiments

In this section we will review the future projects in the $0\nu$-DBD research field either in the R&D phase, or simply submitted proposals; they are ordered following the nuclear mass of the analysed isotope.

(i) Calcium

CANDLES (CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer) is based on the use of CaF$_2$ immersed liquid scintillator at the Oto Cosmo Observatory, in Japan. Several steps have been planned: the CANDLES III setup consists of 60 crystals (3.2 kg each), for a total mass of ~200 kg, and a resolution below 4% at 4.27 MeV. After 3 years of data taking, the sensitivity on $\langle m_\nu \rangle$ will be 0.5 eV. The upgraded setup, called CANDLES IV, consisting of 1000 crystals (3.2 kg each) for a total mass of ~3.2 ton, should reach a $\langle m_\nu \rangle$ limit of 0.150 eV. In the case of $^{48}$Ca enrichment from the natural abundance of 0.18% to 2.0% (called CANDLES V), the limit on the sensitivity will be ~0.030 eV. The same result could be obtained without enrichment, but a total mass of ~50 ton and a low background would be needed [90] [91].

(ii) Germanium

The planned experiments are GENIUS, MAJORANA, and GEM, but in spring 2004 a further project has been presented. For all these ionisation detectors, the cooling
solution is given by using a cryostat, like in MAJORANA, or a liquid Nitrogen bath, in the remaining ones.

- The GENIUS experiment (GERmanium in liquid Nitrogen Underground Setup) would consist of 400 enriched (86 - 88%) HPGe naked crystals, for a total mass of \( \sim 1 \) ton. The detector will be immersed in a liquid nitrogen bath, which also serves as high purity passive shield. To prove the feasibility of this detector, three small naked HPGe crystals have been tested in liquid nitrogen. The result is comparable to that of conventional HPGe diodes (i.e. in vacuum-tight cryostat). The use of naked crystals should move the external radioactivity to outside the liquid nitrogen region. The quoted energy resolution is \( \sim 6 \) keV, while the expected background, which should be maximally due to the external component, is \( \sim 0.0001 \) counts/(keV kg y), and the estimated sensitivity on mass is \( 0.015 - 0.045 \) eV. A test of a naked crystal operating in a liquid nitrogen filled dewar was successful; therefore, a prototype (GENIUS - Test Facility), consisting of 14 naked HPGe crystals was already approved by the LNGS scientific committee.

![Figure 6. Proposed experimental setup for GENIUS detector. An array of 1 ton of enriched \(^{76}\)Ge is hanging on a structure in the middle of a tank filled by liquid nitrogen. The size for this apparatus is greater than 12 m. A clean room and data acquisition room are on the top.](image)

- The MAJORANA setup will consist of 210 86%-enriched HPGe crystals (as segmented diodes) for a total mass of \( \sim 0.5 \) ton, but, unlike GENIUS, very low activity conventional cryostats will be employed. Digital electronics and improved pulse shape discrimination will also be used. The estimated background is \( \sim 7.3 \) counts in an energy region of 3.6 keV, which corresponds to \( \sim 0.0001 \) counts/(keV kg y), and a half-life value of \( \sim 10^{27} \) y at 90% of C.L. The main component of the background reduction will be the granularity of the detector. Among different aspects under analysis, a prototype should check the cooling process for multiple crystals within a single low-background cryostat,
and also the performance in rejecting the background of a segmented detector configuration. Its energy resolution at the Q_{ββ} value is 4 keV. The expected sensitivity for an experimental running time of 10 y is in the 0.030 - 0.040 eV range, \[92\]. The detector is planned to be installed at Waste Isolation Pilot Plant (WIPP), near Carlsbad, in the USA.

![Figure 7. Schematic view of a possible experimental setup for Majorana detector. The external cylindric tanks are liquid nitrogen dewars, whereas inner cylinders are the copper cryostats containing germanium detectors. Lead blocks are also shown.](image)

- The GEM project should use \(\sim 1\) ton of naked HPGe detectors operating in super-high purity liquid nitrogen contained in a copper vacuum cryostat. The detector is within a 5 m diameter sphere placed in a water shield. The first GEM-I phase will employ natural germanium, the GEM-II step will be enriched in \(^{76}\text{Ge}\) at 86\%, \[93\].

- An interesting proposal, which plan to merge, in an unique detector, all the HP\(^{76}\text{Ge}\) elements previously used by IGEX and HM collaborations, has been presented by some members of HM collaboration and other researchers \[94\]. This new apparatus, which could reach an active mass of more than 20 kg, would reside at LNGS. A configuration with a 1.5 m of liquid Nitrogen/liquid Argon shield surrounded by \(\sim 10\) cm of high-purity lead inside the cryostat is under analysis. A further external 2-m of water shield should prevent (and identify) contaminations due to rock and concrete, neutrons and cosmic rays, if photomultipliers are added. If funded, its construction could start in early 2005, whereas its data acquisition could begin in 2006. After 1 year of data taking it could confirm or refuse with a high level of significance the claimed discovery of 0ν-DBD reaction by using the same isotope. As a second step, a further addition of 20 kg of enriched HP\(^{76}\text{Ge}\) is also planned.

(iii) Selenium

SuperNEMO would be an improvement of NEMO-3 detector, with \(\sim 100\) kg of
foils enriched in $^{82}$Se, and better energy resolution. A neutrino mass sensitivity in
the range 0.04 - 0.15 eV is expected, corresponding to a half-life limit greater than
$10^{26}$ y. The proposed apparatus should consist of four sections, each of $\sim 2 \times 3 \times 20$ m$^3$, surrounding the very low radioactive mixture of $^{82}$Se. The electron energy
will be measured by plastic scintillators (having an energy resolution of $\sim 10\%$ at
$E = 1$ MeV), whereas Geiger counters will reconstruct the particle tracks. The use
of $^{100}$ Mo, $^{116}$ Cd and $^{130}$Te isotopes is also possible. A general upgrading of the
underground facilities is still required, see [15].

(iv) Molybdenum
In Japan, the MOON (MOlybdenum Observatory of Neutrinos) experiment will
use $^{100}$Mo as active target, aiming the detection of low energy solar neutrinos (at $E > 168$ keV), and $0\nu$-DBD reactions. The detector is sensitive to $0\nu$-DBD via the
$^{100}$Mo decay to the ground and excited state of $^{100}$Ru. The setup will be a huge
sandwich made by foils of natural molybdenum interleaved with a specially designed
plastic scintillator. The molybdenum total mass will be large, [95]. High purity
levels for the scintillator are needed, and a great effort is required in this sector,
because of the large surface. Other options, such as metal-loaded liquid scintillator
and bolometers, have been analysed. The resolution at the Q-value (3.034 MeV)
should be $\sim 7\%$. Two intermediate steps have been planned to check the feasibility
of the final configuration. An enrichment process has been also considered in order
to reduce the detector dimensions and the internal radioactivity, but it is very
expensive.

(v) Cadmium
The planned experiments are:

- The COBRA (Cadmium-Telluride O neutrino double Beta Research
  Apparatus) collaboration also plans to use $^{130}$Te candidates (and $^{116}$Cd) under
  the form of a new generation of semiconductors. These ionisation detectors,
  which operate at 300 K with an energy resolution of $\sim 1\%$ at the 661 keV line,
  are quite small in size, and allow systematic studies on Cd and Te isotopes,
  and rare beta decays of $^{113}$Cd and $^{123}$Te. Up to now, only 1 cm$^3$ diodes, which
  corresponds to $\sim 6$ g, have been exploited. The COBRA apparatus is planned
  to run with an array of $\sim 15 \times 15$ cm, which corresponds to a mass of $\sim 1.3$
  kg. The detector can be extended by stacking additional modules to form a
tower, and by adding more towers later on, [96].

- CAMEO is an upgraded version of the experiment on $^{116}$Cd performed in
  Solotvina underground laboratory. The initial step will use 24 enriched
cylindrical $^{116}$CdWO$_4$ crystals, with a total mass of 65 kg, and will be placed
  in the middle of the Counting Test Facility (CTF), at LNGS. In order to
  have the required optical coverage, the present number of photomultipliers
  will be doubled. The total background in the energy region of interest has
  been estimated to be $\sim 3$ counts/y. After a measuring time of more than 5
years, a half-life limit of more than $10^{26}$ y will be reached, corresponding to a mass of $\sim 0.060$ eV. In the second step, 370 crystals (for a total mass of $\sim 1$ ton) will be placed within the Borexino apparatus. In this case, the sensitivity will be greater than $10^{27}$ y, and a mass limit in the range of $\sim 0.020$ eV should be reached.

(vi) **Tellurium**

The CUORE (Cryogenic Underground Observatory for Rare Events) project consists of a series of experiments with massive cryogenic detectors to investigate rare processes, in particular the DBD reaction. The final setup of the detector is still under analysis. A possible way-out is a structure with 988 cubic natural TeO$_2$ crystals (5 cm size and a mass of 760 g each), arranged in 19 columns with 12 flows of 4 crystals, operating at $T = 0.01$ K. The total mass will be of 750 kg of TeO$_2$, which corresponds to 203 kg of $^{130}$Te. Crystals will be separated by a few mm of material. The expected background is $\sim 0.001$ counts/(keV kg y), with an energy resolution of $\sim 5$ keV at the Q value (2.529 MeV). The main background component is due to a surface contamination. A great advantage of this experiment is the high natural abundance of $^{130}$Te, moreover cosmogenic activities within the crystals are reduced. The cryostat is also shielded by Roman lead having an activity lower than 4 mBq/kg, surrounded by modern lead, whose activity is $\sim 16$ Bq/kg. The estimated sensitivity is $\sim \sqrt{t} \cdot 10^{26}$ y, where t is the measurement time in year. After 1 year of data taking, the mass limit of 0.04 - 0.15 eV will be available, [60], [86].

(vii) **Xenon**

Two main projects plan to look for $^{136}$Xe.

- The EXO (Enriched Xenon Observatory) experiment should use a new approach that combines quantum optics techniques with radiation detectors, aiming to detect single Ba$^+$ ions, via resonant excitation with a set of lasers, in the final state of $^{136}$Xe DBD. It will use several tons of $^{136}$Xe, enriched up to 80%. The energy resolution will be $\sim 2\%$ at 2.5 MeV. Two different techniques are still under analysis: high pressure gas Time Projection Chamber and liquid Xenon scintillator, which offers much more compact sizes. The EXO collaboration is still preparing a 200 kg prototype detector, [97]. Recently, the required energy resolution has been obtained by simultaneous measurements of ionisation and scintillation light. With a 1 ton detector and 5 y of measurements, a sensitivity of $8 \cdot 10^{26}$ y, or in the mass interval 0.050 - 0.140 eV, is expected. The detector should be installed at WIPP Laboratories in Carlsbad.

- The XMASS (Xenon neutrino MASS detector) experiment will take place at Kamioka Underground Laboratory, Japan. The detector will use liquid Xenon viewed by photomultipliers. In fact, liquid Xenon is a good scintillator, and has a high Z value, density and boiling point. Moreover, Xenon allows purification
**Table 6.** Expected sensitivities and effective neutrino mass limits for future projects. For $\langle m_\nu \rangle$ calculations, the nuclear matrix elements from [107] has been used.

| Experiment     | Isotope | Mass (kg) | $T^{0\nu}_{1/2}$ ($10^{26}$ y) | $\langle m_\nu \rangle$ (eV) | References |
|----------------|---------|-----------|-------------------------------|-----------------------------|------------|
| CAMEO 1+CTF    | $^{116}$Cd | $10^3$    | 10                            | 0.060                       | [100]      |
| CAMEO 2+Borexino | $^{116}$Cd | $10^3$    | 100                           | 0.020                       | [100]      |
| CANDLES        | $^{48}$Ca | $>10^3$   | $>1$                          | 0.030                       | [90]       |
| COBRA          | $^{130}$Te | 10        | 0.01                          | 0.240                       | [101]      |
| CUORE          | $^{130}$Te | 750       | 7                             | 0.027                       | [102]      |
| DCBA           | $^{150}$Nd | 20        | 0.15                          | 0.035                       | [99]       |
| EXO            | $^{136}$Xe | $10^3$    | 8                             | 0.052                       | [97]       |
| GEM            | $^{76}$Ge | $10^3$    | 70                            | 0.018                       | [93]       |
| GENIUS         | $^{76}$Ge | $10^3$    | 100                           | 0.015                       | [103]      |
| MAJORANA       | $^{76}$Ge | 500       | 40                            | 0.030                       | [92]       |
| MOON           | $^{100}$Mo | few $10^3$ | 10                            | 0.036                       | [104]      |
| XMASS          | $^{136}$Xe | $10^4$    | 3                             | 0.086                       | [105]      |

To take place during the operations. An intense R&D phase with a 100 kg detector has confirmed the reliability of vertex and energy reconstruction, the self shielding power for $\gamma$ rays. Then, it has allowed to measure environmental background and internal radioactive impurity. Therefore, a 800 kg detector is currently under construction. The final step will be a 10 ton detector, which should reach a sensitivity of $\sim 8 \cdot 10^{21}$ y for 2$\nu$-DBD and $\sim 3.3 \cdot 10^{26}$ y for 0$\nu$-DBD, which implies a neutrino mass limit of 0.03 - 0.09 eV without enriched materials, [98].

(viii) Neodymium

The DCBA (Drift Chamber Beta-ray Analyser) experiment is searching for 0$\nu$-DBD reaction from $^{150}$Nd. The parameters of this tracking detector, which should be composed by 20 kg of enriched $^{150}$Nd, are under analysis at KEK in Japan, [99]. After a test apparatus for technical development, a standard module, which will use natural Nd as source, will check the feasibility of the whole apparatus, which will consist of a 100 module array with enriched Nd.

Table 6 summarizes the expected sensitivities.

5.1. Other proposals

In the past few years, other approaches have been proposed and developed:

- The use of CTF and/or Borexino apparatuses as 0$\nu$-DBD detector, see [100] [106]
- The use of the SNO detector, after the end of solar neutrinos experiments, filled by a 1% loaded liquid scintillator. An extension of the present underground laboratory (SNO-LAB) has been also proposed to the physics community.
• The systematic studies of $0\nu$-DBD reaction toward excited states of daughter nuclei, see for instance [108], [32], [109], [110], and via $\beta^+$ decays, even if this process offers a reduced phase space and long half-life, see [111]. Another opportunity is given by the radiative neutrinoless double electron capture, see [112], which could be an intriguing sector for isotopes like $^{112}$Sn. The use of doped neodymium crystals has been also recently analysed, see [113]. Unfortunately, the present knowledge of the properties of such nuclei is rough. A strong improvement in nuclear matrix element calculations for both the cases is needed, see [96].

• Search for $0\nu$-DBD reactions of initially unstable nuclei, see [114].

6. Discussion and perspectives

At present, the most powerful results and limits in $0\nu$-DBD experiments have been obtained by detectors using $^{76}$Ge as source (IGEX and HM). They have reached an upper half-life limit of $\sim 1.6 \cdot 10^{25}$y, which corresponds to a sensitivity of $\sim 0.3$ eV, even if nuclear matrix element calculations induce a significant uncertainties in the mass value. Moreover, in spring 2004 the experimental discovery of $0\nu$-DBD reaction in $^{76}$Ge has been claimed, with a half-time $\sim 1.2 \cdot 10^{25}$ y. All these values are beyond the present capability of other experiments, which cannot confirm or deny these results.

The deduced mass value is close to cosmological limits on neutrino masses: WMAP collaboration produces an upper limit of 0.23 eV per neutrino flavour, but this result is strongly dependent on the hypotheses assumed in the calculation, and a more conservative limit is $\sim 0.60$ eV.

Other currently running $0\nu$-DBD experiments, like CUORICINO and NEMO-3, have the possibility to reach and verify this limit within few years of data taking. The KATRIN tritium beta decay apparatus should check this energy region and confirms the recently claimed $0\nu$-DBD experimental discovery.

6.1. Has the $0\nu$-DBD reaction been discovered?

In 2001, some members of the HM collaboration claimed evidence of $0\nu$-DBD at a level of 2.2-3.1 $\sigma$, by assuming a flat background in a small region centred around the Q peak, [40]. Other similar peaks are present in the selected region, and a refined analysis over wide energy region with the inclusion of $^{214}$Bi lines reduced the previous effect at no more than 1.5 $\sigma$. It has to be stressed that the remaining members of HM collaboration did not claim the $0\nu$-DBD discovery in that dataset.

At the beginning of 2004, Klapdor-Kleingrothaus and coll. strongly confirmed the evidence of $0\nu$-DBD process after an analysis on the whole dataset between August 1990 and May 2003, [78]. The main characteristics of the experiment and their results are the following:

• Active volume of 10.96 kg of HP p-type $^{76}$Ge, enriched at 86-88 % level;
• Whole duty cycle of $\sim 80\%$;
Collected statistics of 71.7 kg · y;
Energy resolution at a level of 0.2%;
Background of 0.113 ± 0.007 counts/(keV kg y) in the 0ν-DBD region, around the Q peak, which occurs at 2039.006 ± 0.050 keV;
About $10^6$ events registered since 1995, with new and improved setup;
A signal of 28.75 ± 6.86 events;
When the nuclear matrix calculations given in $[107]$ are used, the $3\sigma$ range results are within the interval $(0.69 - 4.18) \cdot 10^{25}$ y for the half-life, with an effective neutrino mass of 0.24 - 0.58 eV, at 4.2 $\sigma$. The best fit values are $1.19^{+0.37}_{-0.23} \cdot 10^{25}$ y, and 0.44 eV, respectively.

This result is unique and under the analyses of the DBD community. In any case, the identification of a genuine signal in an energy region where background counts are at a similar level is a very difficult task. A confirmation by other experimental groups is needed, even if just the combination of IGEX and HM $^{76}$Ge crystals should verify such results within 2-3 years, by using the same decaying nucleus.

Another consequence of the claimed detection of 0ν-DBD reaction is the necessity to right evaluate the systematic uncertainties, which have usually been estimated as a negligible contribution to the genuine signal.

If the experiments will confirm the quoted half-life and mass values, all particle physics should be renewed, see for instance the references in $[78]$ for an overview.

7. Conclusions

Recent experimental results have shown the neutrinos are changing their flavours when they travel between sources and detectors. The range of values for square mass differences and mixing angles have been deduced. Therefore, neutrino mass eigenstates (at least, two or three, depending on the number of neutrino families) do have a non-zero mass.

Unfortunately, no further news concerning the mass of each term and the neutrino Dirac or Majorana nature is allowed. Neutrinoless DBD is a unique process which could offer an answer to these questions.

New results from cosmology and neutrino mass beta decay based experiments should check the degenerate solution, whereas long baseline experiments could confirm inverted hierarchy spectrum. The KATRIN experiment can test the 0.25 eV mass region within few years.

We also remind that if an established neutrino mass limit is searched for, very different half-life values have to be measured, depending on the selected isotope. As an example, if $|\langle m^\nu \rangle| < 0.04$ eV, the half-life values vary from few $10^{25}$y for $^{150}$Nd up to some $10^{27}$y for $^{48}$Ca, $^{76}$Ge, $^{116}$Cd and $^{136}$Xe, but the selection of a candidate isotope depends on many other parameters.
The actual stronger constraints on neutrino masses are from the cosmological sector, based on WMAP, 2dFGRS, and Lyman-α analyses. The obtained limit $m_1 + m_2 + m_3 < 0.70 - 1.70$ eV implies $|\langle m_{ee}^\nu \rangle| < 0.23 - 0.60$ eV, which has to be compared with the limit quoted in [115].

A common task for all $0\nu$-DBD experimental groups is a further suppression of background events, such as environmental radioactivity, cosmic component, internal contamination. Only a significant reduction of such reactions and an enhancement of genuine signals will allow to measure longer half-lifes, and consequently, smaller neutrinos mass intervals.

The next generation of $0\nu$-DBD detectors, which have an expected sensitivity down to 0.01 eV, should allow the identification of the Dirac or Majorana nature of the neutrino, for the cases of the degenerate and inverted mass spectra, see [116]:

- If the $0\nu$-DBD reaction will be not detected by next-generation experiments and the effective neutrino mass is lower than 0.045 eV, then a normal neutrino mass hierarchy occurs. Consequently, massive neutrinos can be either Dirac or Majorana particles.
- If the $0\nu$-DBD reaction will be observed and the effective mass is greater than 0.045 eV, then the normal hierarchy is excluded.
- If the $0\nu$-DBD reaction will be detected, and $0.4 \sqrt{\Delta m_{atm}^2} \leq |\langle m_\nu \rangle| \leq \sqrt{\Delta m_{atm}^2}$, then an inverted mass hierarchy occurs.
- If the $0\nu$-DBD reaction will be measured, and $|\langle m_\nu \rangle| \gg \sqrt{\Delta m_{atm}^2}$, then the mass spectrum is almost degenerate.
- If future beta decay experiments or cosmological measurements will offer new limits, then the effective neutrino mass will be deduced from the relation $0.4 m_1 \leq |\langle m_\nu \rangle| \leq m_1$. If the $0\nu$-DBD process will not be observed, or if the effective Majorana neutrino mass is out of this range, neutrinos are Dirac particles or other mechanisms producing total lepton number violation are required.

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