SEARCHES FOR NEUTRINOLESS DOUBLE BETA DECAY*

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(Received May 15, 2010)

This paper summarizes the relevance of neutrinoless Double Beta Decay for neutrino physics and the implications of this phenomenon for crucial aspects of particle and astroparticle physics. After discussing general experimental concepts, like the different proposed technological approaches and the sensitivity, the present experimental situation is reviewed. The future searches are then described, providing an organic presentation which picks up similarities and differences. As a conclusion, we try to envisage what we expect round the corner and at a longer time scale.

PACS numbers: 14.60.Pq, 14.60.St

1. Neutrino mass and Double Beta Decay

The Standard Model (SM) of electroweak interactions describes neutrinos as left-handed massless partners of the charged leptons. The experimental identification of the third generation of quarks and leptons completed the model, incorporating also a description of CP violation. The invisible width of the Z boson, caused by its decay into unobservable channels and measured at the e^+–e^- annihilation experiments, show quite confidently that there are just three active neutrinos with masses of less than $M_Z/2$.

We know nowadays that neutrino flavors oscillate. From oscillations, we can evaluate the neutrino mixing matrix. The crucial feature is that unlike quark mixings, neutrino mixings are large. The meaning of this difference is not presently understood. Furthermore, oscillations inform us on mass square differences, not on the masses themselves. We know that they are much smaller than charged lepton masses, but the mass pattern is unknown.

Anyway, the discovery that neutrinos have mass is a breakthrough by itself. It is the first serious crack in the SM building, after 30 years of almost boring successes (although the Higgs boson is still a missing brick).

* Presented at the Cracow Epiphany Conference on Physics in Underground Laboratories and Its Connection with LHC, Cracow, Poland, January 5–8, 2010.

The smallness of the neutrino masses turns out to play a major role in improving our understanding of Grand Unified Theories (GUTs), originated by the efforts to unify the strong and electroweak interactions. Some GUTs allow to explain naturally small neutrino masses — if they are their own antiparticles, a fundamental issue addressed by the study of Neutrinoless Double Beta Decay ($0\nu2\beta$) — and the matter–antimatter asymmetry of the universe via leptogenesis. GUTs have also the potential to provide relations among the quark mixing matrix, the lepton mixing matrix, the quark masses, and the lepton masses. The peculiar properties of neutrinos, and in particular their mass scale, are a crucial challenge for GUTs and for any unified theoretical framework. Therefore, the experimental determinations of the neutrino mass scale, pattern and nature are essential bench tests for predictive GUTs and for the improvement of our understanding of the basic theory of fundamental interactions.

In parallel, the understanding of Big Bang Nucleosynthesis and the features of the Cosmic Microwave Background (CMB) illustrate the important role of neutrinos in the history of the early universe. Neutrino flavor oscillations and other bounds tell us that the heaviest neutrino mass is in the range $0.04 \div 0.6$ eV. Therefore, neutrinos are a component of dark matter, but their total mass, although it outweighs the stars, gives only a minor contribution to invisible matter density. Neutrinos are so light to have streamed freely away from developing aggregations of matter until quite recently (in cosmological terms), when they eventually cooled and their speed has decreased to significantly less than the speed of light. What is then the neutrino role in shaping the universe? Do neutrinos allow to understand the matter–antimatter asymmetry of the universe, via leptogenesis? The answer to these questions requires the precise knowledge of the neutrino mass values.

It is clear therefore that the neutrino mass scale is crucial over two fronts: progress in the comprehension of elementary particles and solution of hot astroparticle and cosmological problems. The studies of $0\nu2\beta$ and end-point anomalies in β decay, in particular, are essential and unique in their potential to fix the neutrino masses and to answer key-questions beyond neutrino physics itself. Both types of measurements will be required to fully untangle the nature of the neutrino mass.

1.1. Neutrino flavour oscillations and neutrino mass

Neutrino oscillations can take place since the neutrinos of definite flavor (ν_e, ν_μ, ν_τ) are not necessarily states of a definite mass (ν_1, ν_2, ν_3). On the contrary, they are generally coherent superpositions of such states:

$$|\nu_l\rangle = \sum_i U_{li}|\nu_i\rangle\,. \tag{1}$$

When the SM is extended to include neutrino mass, the mixing matrix U is unitary. As a consequence, the neutrino flavor is no longer a conserved quantity and for neutrinos propagating in vacuum the amplitude of the process $\nu_l \rightarrow \nu_{l'}$ is not vanishing.

The probability of the flavor change is the square of this amplitude. Due to the unitarity of U there is no flavor change if all masses vanish or are exactly degenerate. The idea of oscillations was discussed early on by Pontecorvo, and by Maki, Nakagawa and Sakata. Hence, the mixing matrix U is often associated with these names and the notation $U_{\rm MNS}$ or $U_{\rm PMNS}$ is used. In general, the mixing matrix of 3 neutrinos is parametrized by three angles, conventionally denoted as Θ_{12}, Θ_{13} and Θ_{23}, one CP-violating phase δ and two Majorana phases α_1, α_2. The three neutrino masses m_i have to be added to the parameter set that describes this matrix, giving therefore nine unknown parameters altogether. The evidence for oscillations of solar (ν_e) and atmospheric (ν_μ and $\overline{\nu}_\mu$) neutrinos is compelling and generally accepted.

Two of the three angles and the two mass square differences have been determined reasonably well. The unknown quantities, subjects of future oscillation experiments, are the angle Θ_{13} and the sign of Δm^2_{13}. If that sign is positive, the neutrino mass pattern is called a normal mass ordering ($m_1 < m_2 < m_3$) and when it is negative it is called inverted mass ordering ($m_3 < m_1 < m_2$). The extreme mass orderings, $m_1 < m_2 \ll m_3$ and $m_3 \ll m_1 < m_2$, are called the normal and, respectively, inverted hierarchies. When $m_1 \sim m_2 \sim m_3$, one speaks of degenerate pattern. In addition, the phase δ governing CP violation in the flavor oscillation experiments remains unknown, and a topic of considerable interest. The remaining unknown quantities, *i.e.* the absolute neutrino mass scale and the two Majorana phases α_1, α_2, are not accessible in oscillation experiments. Their determination is the ultimate goal of $0\nu2\beta$ and β decay experiments.

1.2. The neutrino mass scale: a threefold concept

Three methods can address directly the neutrino mass scale: analysis of CMB temperature fluctuations [1], Double Beta Decay [2] and single beta decay [3]. The quantities probed in these three approaches are however different, and are given respectively by:

$$\begin{aligned} m_{\rm cosm} &= \sum_{i=1}^{3} m_i\,, \\ m_{\beta\beta} &= \left|\sum_{i=1}^{3} |U_{ei}|^2 m_i e^{i\alpha_i}\right|\,, \qquad m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}\,. \end{aligned} \tag{2}$$

The first method is observational, and performs a purely kinematical estimation of the neutrino masses. Even if very sensitive, it depends critically on cosmological and astrophysical assumptions and requires therefore independent checks. The second and third methods are based on laboratory searches. The $0\nu2\beta$ provides at the moment a sensitivity in the range $0.2 \div 1.0$ eV, with an uncertainty dominated by nuclear physics aspects. This process does not occur if the neutrino is a Dirac particle, *i.e.* if it is not self-conjugate. Single beta decay endpoint measurements, frequently referred to as "direct searches" for neutrino mass, are essentially free of theoretical assumptions about neutrino properties and are almost fully model-independent. The present limit achieved by this approach is 2.2 eV. The past and any future conceivable experiments are not able to disentangle the three values of the neutrino masses (although this operation would be possible in principle) because the required energy resolution and statistics are out of the reach of the present techniques. That is why single beta decay is sensitive only to a weighted average of the mass eigenvalues, expressed by the second expression in Eq. (2).

It is important to stress that the *parallel* study of the three discussed variants of the mass scale is a crucial task. The parameters in Eq. (2) depend on different combinations of the neutrino mass values and oscillation parameters. The $0\nu2\beta$ decay rate is proportional to the square of a *coherent* sum of the Majorana neutrino masses because the process originates from exchange of a *virtual* neutrino. On the other hand, beta decay determines an *incoherent* sum because a *real* neutrino is emitted. In cosmology, the three masses play a kinematical role and the mechanisms of weak interactions are not relevant, therefore the testable parameter is a *pure sum.* That shows clearly that a complete neutrino physics program should renounce none of these three observational/experimental approaches, which are not redundant but rather complementary. They are all required to fully untangle the nature of the neutrino mass.

The $0\nu2\beta$ decay [2] is a rare nuclear process consisting in the simultaneous transformation of two neutrons into two protons in a nucleus, with the emission of two electrons and nothing else. One can visualize it by assuming that the process involves the exchange of proper virtual particles between two single-beta-decay-like vertices, *e.g.* light or heavy Majorana neutrinos, SUSY particles, and other more exotic options. Of primary interest is the process mediated by the exchange of light Majorana neutrinos interacting through the left-handed V–A weak currents. The decay rate is then

$$\left(T_{0\nu}^{1/2}\right)^{-1} = G_{0\nu}(Q,Z)\, M_{0\nu}\, m_{\beta\beta}^2 \,, \tag{3}$$

where $G_{0\nu}$ is the accurately calculable phase space integral (growing with the transition energy Q approximately as Q^5), $m_{\beta\beta}$ is the effective neutrino mass (as defined by the second expression in Eq. (2)), and $M_{0\nu}$ the nuclear matrix elements. If the $0\nu 2\beta$ decay is observed, and the nuclear matrix elements are known, one can deduce the corresponding $m_{\beta\beta}$ value.

Due to the presence of the unknown Majorana phases α_i, cancellation of terms is possible, and $m_{\beta\beta}$ could be smaller than any of the m_i. Thanks to the information we have from oscillations, it is useful to express $m_{\beta\beta}$ in terms of three unknown quantities: the mass scale, represented by the mass of the lightest neutrino $m_{\min}$, and the two Majorana phases. It is then useful to distinguish the already discussed three mass patterns: normal hierarchy (NH), inverted hierarchy (IH), and the quasi-degenerate spectrum (QD) where $m_{\min} \gg \sqrt{|\Delta m^2_{31}|}$ as well as $m_{\min} \gg \sqrt{|\Delta m^2_{21}}$.

In the case of normal hierarchy, and assuming that $m_1 = m_{\min}$ can be neglected, $\Theta_{13} = 0$ and inserting the parameters as presently known from the analysis of the oscillation experiments, one obtains $m_{\beta\beta} = 2.6 \pm 0.3$ meV. On the other hand, there are possible combinations of Θ_{13}, Θ_{12}, Δm^2_{31} and Δm^2_{21} which provide a partial or complete cancellation, leading to a vanishing $m_{\beta\beta}$. Not only, if $m_{\min} > 0$ then $m_{\beta\beta}$ may vanish even for $\Theta_{13} = 0$. In the case of the inverted hierarchy, and again assuming that $m_3 = m_{\min}$ can be neglected, $\Theta_{13} = 0$ and inserting the oscillation-derived parameters, one obtains $m_{\beta\beta} \simeq 14 \div 51$ meV, depending on the Majorana phases. Finally, for the quasi-degenerate spectrum, m_0 being the common mass value and making the same assumption as above, $m_{\beta\beta} \simeq (0.71 \pm 0.29) m_0$. For a discussion on the neutrino mass ordering, the Majorana phases and $m_{\beta\beta}$, see for example [4].

If one can experimentally establish that $m_{\beta\beta} \geq 50$ meV, one can conclude that the QD pattern is the correct one, and one can extract an allowed range of $m_{\min}$ values. On the other hand, if $m_{\beta\beta}$ lies in the range 20–50 meV, only an upper limit for $m_{\min}$ can be established, and the likely pattern is IH, even though exceptions exist. Eventually, if one could determine that $m_{\beta\beta} < 10$ meV but non-vanishing (which is unlikely in a foreseeable future), one could conclude that the NH pattern is the correct one.

Altogether, observation of the $0\nu 2\beta$ decay, and an accurate determination of the $m_{\beta\beta}$ value, would not only establish that neutrinos are massive Majorana particles, but would contribute considerably to the determination of the absolute neutrino mass scale. Moreover, if the neutrino mass scale would be known from independent measurements, one could possibly obtain also some information about the CP-violating Majorana phases from the measured $m_{\beta\beta}$.

2. Experimental challenge and strategies

When generically speaking of Double Beta Decay, one refers to a rare nuclear transition proposed for the first time by Göppert–Mayer in the far 1935. In this process, a metastable isobar changes into a more stable one by the simultaneous emission of two electrons. Such transition can take place in principle for 35 naturally occurring even–even nuclei, whose ordinary β decay is forbidden energetically or severely hindered by a large change of the nuclear spin-parity state. Double Beta Decay is a second-order process of the weak interaction and has consequently a very low probability, which leads to extraordinary long lifetimes for the candidate nuclides.

Two decay modes are usually discussed. The two-neutrino process ($2\nu 2\beta$), already observed in several nuclides, is described by

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^- + \overline{\nu}_1 + \overline{\nu}_2 \tag{4}$$

and is fully consistent with the SM. The neutrinoless channel ($0\nu 2\beta$)

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^- \tag{5}$$

violates lepton number conservation and, as already discussed, would definitely imply new physics beyond the SM. The available phase space is significantly larger for this process than for the 2ν channel.

2.1. Experimental approaches and methods

From the experimental point of view, the shape of the two electron sum energy spectrum enables to distinguish among the two discussed decay modes. In the case of $2\nu 2\beta$ — process of Eq. (4) — this spectrum is expected to be a continuum between 0 and Q with a maximum around $1/3Q$. For $0\nu 2\beta$ — process of Eq. (5) — the spectrum is just a peak at the energy Q, enlarged only by the finite energy resolution of the detector. Additional signatures are the single electron energy distribution and the angular correlation between the two emitted electrons. Q ranges from 2 to 3 MeV for the most promising candidates.

The experimental strategy pursued to investigate the $0\nu 2\beta$ decay consists of the development of a proper nuclear detector, with the purpose to reveal the two emitted electrons in real time and to collect their sum energy spectrum as a minimal information. Additional pieces of information can be provided in some cases, like single electron energy and initial momentum, or, in one proposed approach, the species of the daughter nucleus. The desirable features of this nuclear detector are:

- High energy resolution, since a peak must be identified over an almost flat background in the case of $0\nu 2\beta$.

- Low background, which requires underground detector operation (to shield cosmic rays), very radiopure materials (the competing natural radioactivity decays have typical life-times of the order of 10^9, 10^{10} years *versus* lifetimes longer than 10^{25} years for $0\nu 2\beta$), and well designed passive and/or active shielding against local environmental radioactivity.

- Large source, in order to monitor many candidate nuclides. Present sources are of the order of 10 kg in the most sensitive detectors, while the next generation experiments aim at sources in the $100 \div 1000$ kg scale.

- Event reconstruction method, useful to reject background and to provide additional kinematical information on the emitted electrons.

Normally, the listed features cannot be met simultaneously in a single detection method. It is up to the experimentalist to choose the philosophy of the experiment and to select consequently the detector characteristics, privileging some properties with respect to others, having in mind, of course, the final sensitivity of the set-up to half-life and to $m_{\beta\beta}$.

The searches for $0\nu 2\beta$ can be further classified into two main categories: the so-called calorimetric technique, in which the source is embedded in the detector itself, and the external-source approach, in which source and detector are two separate systems.

The **calorimetric technique** has been proposed and implemented with various types of detectors, such as scintillators, bolometers [6], solid-state devices [7] and gaseous chambers. There are positive (+) and negative (–) features in this technique, here summarized:

– There are severe constraints on detector material and therefore on the nuclides that can be investigated;

+ Due to the intrinsically high efficiency of the method, large source masses are possible: ~10 kg have been demonstrated, ~1000 kg are planned;

+ With a proper choice of the detector, a very high energy resolution (of the order of 0.1 %) is achievable, as in Ge-diodes or in bolometers;

– It is difficult to reconstruct event topology, with the exception of liquid or gaseous Xe TPC, but at the price of a lower energy resolution.

For the **external-source approach** many different detection techniques have been experimented as well: scintillation, gaseous TPCs, gaseous drift chambers, magnetic field for momentum and charge sign measurement, time-of-flight. These are the main features, with their positive or negative valence:

– Large source masses are not easy to achieve because of self-absorption in the source, so that the present limit is around 10 kg;

– Normally the energy resolution is low (of the order of 10 %), intrinsically limited by the fluctuations of the energy the electrons deposite in the source itself;

\+ Neat event reconstruction is possible, allowing to achieve a virtual zero background: however, $0\nu2\beta$ cannot be distinguished by $2\nu2\beta$ event by event if the total electron energy is around Q; therefore, because of the low energy resolution, $2\nu2\beta$ constitutes a severe background source for $0\nu2\beta$.

2.2. The experimental sensitivity

In order to compare different experiments, it is useful to give an expression providing the sensitivity of an experimental set-up to the $0\nu2\beta$ lifetime of the investigated candidate, and hence to determine the sensitivity to $m_{\beta\beta}$. The first step involves only detector and set-up parameters, while for the second step one needs reliable calculations of the nuclear matrix elements. The sensitivity to lifetime F can be defined as the lifetime corresponding to the minimum detectable number of events over background at a 1 σ confidence level. For the case of a source embedded in the detector and non-zero background, it holds:

$$F = \frac{N_{\mathrm{A}}\varepsilon\,\eta}{A}\left(\frac{M\,T}{b\Delta E}\right)^{1/2}, \tag{6}$$

where N_{A} is the Avogadro number, M the detector mass, ε the detector efficiency, η the ratio between the total mass of the candidate nuclides and the detector mass, ΔE the energy resolution, and b the specific background, *e.g.* the number of spurious counts per mass, time and energy unit.

From this formula one can see that, in order to improve the performance of a given set-up, one can use either brute force (*e.g.* increasing the exposition $M\,T$) or better technology, improving detector performance (ΔE) and background control (b). Next generation experiments require to work on both fronts.

In order to derive the sensitivity to $m_{\beta\beta}$, indicated as $F_{m_{\beta\beta}}$, one must combine Eq. (6) with Eq. (3), obtaining

$$F_{m_{\beta\beta}} \propto \frac{1}{(G_{0\nu}(Q,Z))^{\frac{1}{2}}|M^{0\nu}|}\left(\frac{b\,\Delta E}{M\,T}\right)^{1/4} \tag{7}$$

which shows how the nuclide choice is more relevant than the set-up parameters, on which the sensitivity depends quite weakly.

Nowadays, several experimental techniques promise to realize zero background investigations in the close future. In this circumstance, Eqs. (6) and (7) do not hold anymore. The observation of 0 counts exclude N_b counts at a given confidence level. For instance, $N_b = 3$ is excluded at the 95% C.L. in a Poisson statistics. Therefore, the sensitivity F_0 for a 0 background experiment is given by

$$F_0 = \frac{N_{\mathrm{A}} \varepsilon \, \eta}{A} \frac{M \, T}{N_b} \,, \qquad (8)$$

and Eq. (7) modifies accordingly.

Uncertainties coming from nuclear matrix element calculations prevent for the moment from determining precise $m_{\beta\beta}$ values in correspondence of a given lifetime. Large spreads in the lifetime predictions for the same $m_{\beta\beta}$, even more than one order of magnitude, existed in the past. Recently, signs of convergence within different schools showed up. For the evaluation of the sensitivities, it is recommendable to neglect old calculations and to use the results of the still active authors, who go on refining the nuclear models and considering new effects. In particular, four active schools should be considered. Two of them base their calculation on the QRPA method [8, 9], while a third one uses the Interactive Shell Model (ISM) [10]. Recently, a new formalism was proposed for calculating nuclear matrix elements of neutrinolesse Double Beta Decay within the framework of the microscopic interacting boson model (IBM 2). It is remarkable that there is a somewhat surprising good agreement between QRPA and IBM 2.

3. Present experimental situation

We are at a turning point in the experimental search for Double Beta Decay. Few experiments have given limits on $m_{\beta\beta}$ of about 0.5–1 eV, but they are either over or close to their final sensitivity. On the contrary, several next generation projects, which are in the construction or in the research and development phase, have the potential to improve present limits and to approach to the IH region of the neutrino mass pattern.

3.1. The Heidelberg–Moscow experiment

In the ninties of last century, the Double Beta Decay scene was dominated by the Heidelberg–Moscow (HM) experiment [14]. This search was based on a set of five Ge-diodes, enriched in the candidate isotope ^{76}Ge at 86%, and operated underground with high energy resolution (typically, 4 keV FWHM) in the Laboratori Nazionali del Gran Sasso (LNGS), Italy. This search can be considered, even from the historical point of view, as the paradigm of the calorimetric approach discussed in Sec. 2. The total mass of the detectors is 10.9 kg, corresponding to a source strength of 7.6×10^{25} ^{76}Ge nuclei, the largest in DBD searches so far. The raw background, impressively low, is 0.17 counts/(keV kg y) around Q (2039 keV). It can be reduced by a further factor 5 using Pulse Shape Analysis to reject multi-site events. The limits on half-life and $m_{\beta\beta}$ are respectively 1.9×10^{25} y and $0.3 \div 0.6$ eV (depending on the nuclear matrix elements chosen for the analysis).

A subset of the HM Collaboration has however claimed the discovery of $0\nu2\beta$ decay in 2001, with a half-life best value of 1.5×10^{25} y ($(0.8 \div 18.3) \times 10^{25}$ y at 95% C.L.), corresponding to a best value for $m_{\beta\beta}$ of 0.39 eV ($0.05 \div 0.84$ eV at 95% C.L. including nuclear matrix element uncertainty) [15]. This claim is based on the identification of tiny peaks in the region of the $0\nu2\beta$ decay, one of which occurs at the ^{76}Ge Q-value. However, this announcement raised skepticism in the Double Beta Decay community [16], including a part of the HM Collaboration itself [17], due to the fact that not all the claimed peaks could be identified and that the statistical significance of the peak looked weaker than the claimed 2.2 σ and dependent on the spectral window chosen for the analysis [18, 19]. However, new papers [20] published later gave more convincing supports to the claim. The quality of the data treatment improved and the exposure increased to 71.7 kg y. In addition, a detailed analysis based on Pulse Shape Analysis suggests that the peak at the ^{76}Ge Q-value is mainly formed by single-site events, as expected in the case of Double Beta Decay, while the nearby recognized γ peaks are compatible with multi-site events, as expected from γ interaction in that energy region and for detectors of that volume. A 4.2 σ effect is claimed. Unfortunately, the HM experiment is now over and the final word on this crucial result will be given by other searches.

3.2. The NEMO3 experiment

The top level of the external-source technique was reached nowadays by the NEMO3 experiment. The NEMO3 detector, installed underground in the Laboratoire Souterrain de Modane (LSM), in France, is based on well established technologies in experimental particle physics: the electrons emitted by the sources cross a magnetized tracking volume instrumented with Geiger cells and deliver their energy to a calorimeter based on plastic scintillators. Thanks to the division in 20 sectors of the set-up, many nuclides can be studied simultaneously, such as ^{100}Mo, ^{82}Se, ^{150}Nd, ^{116}Cd, ^{130}Te, ^{96}Zr, ^{48}Ca. Presently, the strongest source is ^{100}Mo with 4.1×10^{25} nuclei. The energy resolution ranges from 11% to 14.5%. Results achieved with ^{100}Mo fix the half-life limit to 5.8×10^{23} y, corresponding to limits of $0.8 \div 1.3$ eV on $m_{\beta\beta}$ [13]. The final sensitivity to this parameter is $0.1 \div 0.3$ eV. In NEMO3 experiment, all the best and all the limits of the external-source approach show off. From one side, the NEMO3 detector produces beautiful reconstruction of the sum and single electron energy spectrum, and precious information about angular distribution. Double Beta Decay events can be neatly reconstructed with almost no competing background. Thanks to the multi-source approach, $2\nu2\beta$ decay has been detected in all the seven candidates under observation, a superb physical and technical achievement which makes the NEMO3 set-up a real "Double Beta factory". On the other hand, the low energy resolution and the unavoidable "bi-dimensional" structure of the sources make a further improvement of the sensitivity to $0\nu2\beta$ quite difficult, because of the background from $2\nu2\beta$ and of the intrinsic limits in the source strength.

3.3. The CUORICINO experiment

Bolometric detection of particles [5] is a technique particularly suitable to $0\nu2\beta$ search, providing high energy resolution and large flexibility in the choice of the sensitive material [6]. It can be considered the most advanced and promising application of the calorimetric approach. In bolometers, the energy deposited in the detector by a nuclear event is measured by recording the temperature increase of the detector as a whole. In order to make this tiny heating appreciable and to reduce all the intrinsic noise sources, the detector must be operated at very low temperatures, of the order of 10 mK for large masses. Several interesting bolometric candidates were proposed and tested. The choice has fallen on natural TeO_2 (tellurite) that has reasonable mechanical and thermal properties together with a very large (27% in mass) content of the 2β-candidate ^{130}Te. This property makes the request of enrichment not compulsory, as it is for the other interesting isotopes. Moreover, the reasonably high transition energy (2530 keV) and the favorable nuclear matrix elements make this nuclide one of the best candidate for $0\nu2\beta$ search. A large international collaboration has been running an experiment for five years, named CUORICINO (which means in Italian "small CUORE — heart"), now stopped, which was based on this approach and was installed underground in the Laboratori Nazionali del Gran Sasso [12]. CUORICINO consisted of a tower of 13 modules, containing 62 TeO_2 crystals for a total mass of $\sim$41 kg, corresponding to a source strength of 5.0×10^{25} ^{130}Te nuclei. CUORICINO results are at the level of the HM experiment in terms of sensitivity to $m_{\beta\beta}$, covering a range of limits of $0.2\div0.7$ eV, depending on the choice of the nuclear matrix elements. A very low background (of the order of 0.18 counts/(keV kg y)) was obtained in the $0nu2\beta$ decay region, similar to the one achieved in the HM set-up. The energy resolution is about 8 keV FWHM, quite reproducible in all the crystals. Unfortunately CUORICINO, despite a sensitivity comparable to that of the HM experiment, cannot disprove the ^{76}Ge claim due to the discrepancies in the nuclear matrix element calculations.

4. The future projects and the related technologies

4.1. Selection of the candidates and of the technologies

Due to the importance of the subject for neutrino and fundamental physics, strong efforts are produced all over the world to increase the sensitivity in the search for $0\nu2\beta$ decay. The general goal of these experimental developments is to reach a sensitivity able in a first phase to approach the IH region of the neutrino mass pattern, *i.e.* $m_{\beta\beta} \sim 50$ meV, and in a second phase to cover fully this region, *i.e.* $m_{\beta\beta} \sim 20$ meV. Some general considerations apply to all the future searches. First, the importance to get a high Q-value, in terms both of the phase space for the process and of the impact of the γ background, limit substantially the number of candidate nuclei that are experimentally relevant. The list of the nuclei which are taken into consideration for future searches is reported in Table I with their basic features, including the $m_{\beta\beta}$ estimations according to the three most active schools in nuclear-matrix-element calculations, designated as QRPA-1 [8], QRPA-2 [9] and ISM [10].

TABLE I

Properties of the most relevant candidates for $0\nu2\beta$ decay search. The ranges of $m_{\beta\beta}$ values are calculated assuming 10^{27} y half-life, using the results of the four most active schools in nuclear-matrix-element calculations [8–11]. The maximum in the range corresponds usually to the Shell Model calculation when present, which generally predicts lower rates. The calculations for ^{100}Mo, ^{116}Cd and ^{150}Nd have not been performed with the Shell Model, while this approach is the only one used for ^{48}Ca. The calculation for ^{150}Nd is performed only with the Interactive Boson Model and is complicated by the effects of nuclear deformation. It could be less reliable than for the other nuclides.

Candidate nucleus	I.A. [%]	Q-value [keV]	Number of nuclei in 1 ton [$\div 10^{27}$]	$m_{\beta\beta}$ range [meV] [8–11]
^{130}Te	33.8	2527	4.6	16–37
^{116}Cd	7.5	2802	5.2	18–32
^{76}Ge	7.8	2039	7.9	32–88
^{136}Xe	8.9	2479	4.4	24–44
^{82}Se	9.2	2995	7.3	17–45
^{100}Mo	9.6	3034	6.0	15–34
^{150}Nd	5.6	3367	4.0	15
^{48}Ca	0.187	4270	12.5	75–104

Secondly, given the best estimations of the nuclear matrix elements and the phase space factors, which grow quickly with the Q-value, it is easy to show that, for practically all the nuclei of interest, approaching the inverted hierarchy region means to search for $1\div10$ counts/y/ton, while fully covering it means to be sensitive to $0.1\div1$ counts/(y ton). This fixes immediately the size of the future experiments (from hundreds of kg to 1 ton of isotope) and the level of the requested background (that should be 0 or a very few counts in the region of interest for the total duration of the experiment, normally a few years). In a high energy-resolution experiment (with $\Delta E_{\mathrm{FWHM}} \sim 1$ keV) this request translates into a specific background coefficient b of the order of 1 counts/(keV y ton), while the target is even more ambitious for low energy-resolution search, where however the most critical role is played by $2\nu2\beta$ decay. When designing a future Double Beta Decay experiment and selecting a detector technology for it, the experimentalist should therefore ask himself or herself three basic questions, the answer to which must be "yes" if that technology is viable and timely:

1. Is the selected technology able to deal with 1 ton of isotope, at least in prospect?
2. Is the choice of the detector and of the related materials compatible with a background of the order of at most 1 counts/(y ton) in the region of interest?
3. Can the experiment be designed and constructed in a few years, and can the chosen technique provide at least 80% live time for several years?

The first question needs to be considered also from the economical point of view. As Table I shows, practically all the nuclei of interest, with the significant exception of ^{130}Te, require isotopical enrichment. The cost of this process, when technically feasible, is in the range $20\div200$ \$/g. Therefore, a next generation $0\nu2\beta$ experiment has a cost in the range of several tens of millions of dollars, just to get the basic material. Let us see now which solutions are under test worldwide to get a positive answer to the three questions listed above.

4.2. Classification and overview of the experiments

As already discussed in Sec. 2, two approaches are normally followed in $0\nu2\beta$ decay experiments (calorimetric technique and external source) and two classes of searches can be singled out in terms of detector performance (high energy resolution without tracking capability and low energy resolution with event topology reconstruction). This classification applies also to future searches. I will schematically review fourteen projects, which are reported in Fig. 1 and grouped in four categories in relation with the approaches and the performance mentioned above.

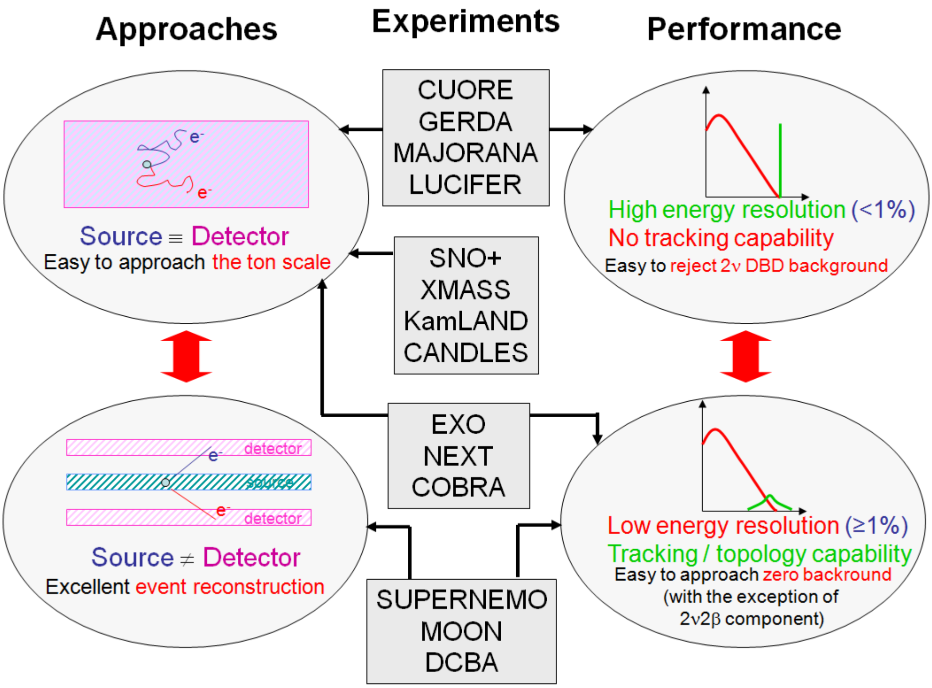

Fig. 1. The most relevant projects are classified in four categories, according to the basic approach adopted and to the detector performance expected.

The **first category** is characterized by a calorimetric approach with high energy resolution, with four planned projects.

CUORE [21], a natural expansion of CUORICINO, will be an array of natural TeO_2 bolometers arranged in 19 towers and operated at 10 mK. The source will correspond to 200 kg of the isotope ^{130}Te. It will take advantage of the CUORICINO experience and will be located in LNGS, Italy. The proved energy resolution is 0.25% FWHM. The sensitivity to $m_{\beta\beta}$ is $\sim$ 50 meV. CUORE is in the construction phase and data taking is foreseen to start in 2013. A general test of the CUORE detector, comprising a single tower and named CUORE-0, will take data in 2011.

GERDA [22] will be an array of enriched Ge diodes operated in liquid argon and investigating the isotope ^{76}Ge. The proved energy resolution is 0.16% FWHM. The first phase (2010) consists of 18 kg of isotope, and the experiment is located in LNGS, Italy. The second phase foresees 40 kg of isotope. The predicted sensitivity to $m_{\beta\beta}$ is $\sim$ 350 meV in the first phase (scrutiny of the ^{76}Ge claim is imminent), and 100÷300 meV in the second phase. The first phase set-up is in an advanced construction stage and data taking is foreseen for summer 2010.

MAJORANA [23] is an array of enriched Ge diodes operated in conventional Cu cryostats and investigating the isotope ^{76}Ge. It has a modular structure and the first step envisages 2 modules of 60 kg each. The proved energy resolution is 0.16% FWHM. It is in the research and development phase. Merging with GERDA is foreseen in view of a 1 ton set-up.

LUCIFER [24] is a project funded through ERC Advanced Grants of the European Commission (2010). It will consist of an array of ZnSe scintillating bolometers operated at 20 mK. The proof of principle with $\sim$10 kg enriched Se is foreseen in 2014. The proved energy resolution is better than 1% FWHM. LUCIFER is in the research and development phase, and can be considered as a demonstrator for a possible upgrade of CUORE, with however a considerable sensitivity by itself ($\sim$ 60 meV).

Even though these experiments do not have tracking capability, some space information and other tools help in reducing the background. An important asset is granularity, which is a major point for CUORE (array of 988 closely-packed individual bolometers), MAJORANA (a set of modules with 57 closely-packed individual Ge diodes per module) and the lower energy resolution experiment COBRA, discussed later (in the final design, 64 000 individual semiconductor detectors). Granularity provides a substantial background suppression thanks to the rejection of simultaneous events in different detector elements, which cannot be ascribed to a $0\nu2\beta$ process.

Another tool which can improve the sensitivity of Ge-based calorimetric searches are Pulse Shape Analysis, already used in the HM experiment with remarkable results. It is well known that in ionization detectors one can achieve spatial information looking at the pulse shape of the current pulse. This fact will be exploited in GERDA and in MAJORANA. Space resolution can be substantially improved by segmentation and pixellization of the readout electrodes in semiconductor detectors. A significant research and development activity on this subject is in progress in GERDA, MAJORANA and COBRA.

Other techniques to suppress background in calorimetric detectors are sophisticated forms of active shielding. For instance, the operation of the GERDA Ge diodes in liquid argon opens the way, in a second phase of the experiment, to the use of the cryogenic liquid as a scintillating active shield. In bolometers, it was clearly shown that additional bolometric elements thermally connected to the main detector in the form of thin slabs can identify events due to surface contamination [25]. This is a particularly dangerous background source, presently the most limiting factor in the CUORE predicted performance, since surface α's, degraded in energy, populate the spectral region of interest for $0\nu2\beta$ decay. This shows that several refinements are possible in the high-energy-resolution calorimetric experiments, and that an important research and development activity is mandatory to improve the sensitivity of next-generation experiments.

A very promising development of the calorimetric approach realized by means of low-temperature detectors consists in the realization of scintillating bolometers [26]. This technology is at the basis of the LUCIFER project [24]. The simultaneous detection of heat and scintillation light for the same event allows to reject α particles with efficiency close to 100%, since the ratio between the photon and phonon yield is different for α and for γ/β interactions. In addition, rejection by Pulse Shape Analysis looks possible in some cases both in the heat and light channel. The α rejection capability becomes formidably promising when applied to candidates with a Q-value higher than 2.6 MeV, *i.e.* outside the natural γ radioactivity range, since in this case αs are the only really disturbing background sources. A complete elimination of αs for these candidates could easily lead to specific background levels of the order of $10^{-4}\div10^{-5}$ counts/keV/kg/y, one or two orders of magnitude better than the presently best estimations for future searches. A research program in this field, partially already accomplished, has identified promising scintillating compounds of ^{48}Ca, ^{100}Mo, ^{116}Cd and ^{82}Se, such as $PbMoO_4$, $CdWO_4$, $CaMoO_4$, $SrMoO_4$, $ZnMoO_4$,CaF_2 and ZnSe. The choice of LUCIFER has fallen on ZnSe, because of the favourable mass fraction of the candidate, the availability of large radiopure crystals and the well established enrichment/purification technology for Se.

The **second category** of future experiments (calorimetric search with low energy resolution and no tracking capability) is represented by four samples which exploit different techniques and solve the low-energy-resolution problem with diverse measures.

SNO+ [29] is an upgrade of the solar neutrino experiment SNO (Canada), aiming at filling the SNO detector with Nd-loaded liquid scintillator to investigate the isotope ^{150}Nd. Crucial points are Nd enrichment and purity, Another issue concerns the ^{150}Nd nuclear matrix elements, whose calculation is made difficult by nucleus deformation, which could lead to an important suppression. The present plan is to use 0.1% w/w natural Nd-loaded liquid scintillator in 1000 tonnes, providing a source of 56 kg ^{150}Nd, which should guarantee a sensitivity of 100–200 meV to $m_{\beta\beta}$. A very large statistics and a full comprehension of the background sources can compensate the low energy resolution. The Double Beta Decay peak will emerge in the residuals of the background fit. SNO+ is in construction phase with natural neodymium. Data taking is foreseen in early 2012.

XMASS [27] is a multipurpose scintillating liquid Xe detector (dark matter, $0\nu2\beta$ decay, solar neutrinos) to be installed in Kamioka, Japan, for the investigation of the isotope ^{136}Xe. Three development stages are foreseen: 3 kg (prototype) — 1 ton — 10 tons. In the $0\nu2\beta$ option, the efforts will be directed to a low background in the MeV region. A special test is in progress with an eliptic water tank to shield high energy gamma rays.

High light yield and collection efficiency can provide high energy resolution down to 1.4% (control of 2ν background). The target is to cover IH region with 10 ton natural or 1 ton enriched. Presentlly the experiment is in an research and development phase for the $0\nu 2\beta$ decay version.

KamLAND [30] is an upgrade of the KamLAND set-up. The idea is to convert it to neutrinoless Double Beta Decay search by dissolving Xe gas in the liquid scintillator (feasible at 2% w/w in a straightforward manner and capable to scrutinize the ^{76}Ge claim), or to load the liquid scintillator with neodynium at 1% w/w as in SNO+ (this requires research and development, but it is more competitive since the sensitivity could be as low as 50 meV). Research and development to improve light yield of scintillator by 50% is ongoing.

CANDLES is an array of natural pure (not Eu doped) CaF_2 scintillators, aiming at the investigation of the isotope ^{48}Ca. The prove of principle has been completed (CANDLES I and II), with a prototype set-up in Kamkioka. Next step (CANDLES III) consists of 191 kg divided in 60 crystals read out by 40 PMT. A further step (CANDLES IV), requiring intense research and development, foresees 6.4 tons divided in 600 crystals, for a total of 6.4 kg of ^{48}Ca. The final ambitious goal (CANDLES V) is 100 ton (speculated insertion in SNO or Kamland). The proved energy resolution is 3.4% FWHM (extrapolated from 9.1% at 662 keV). The good point of CANDLES is the high Q-value of ^{48}Ca: 4.27 MeV, out of γ (2.6 MeV end point), β (3.3 MeV end point) and α (max 2.5 MeV with quench) natural radioactivity. Other background cuts come from Pulse Shape Analysis (α/β different timing) and space-time correlation for Bi–Po and Bi–Tl sequences. A further good point is the special arrangement of the scintillating crystals, which are surrounded by two liquid scintillators envelopes: an internal one which acts as a wavelength shifter for the UV light emitted by the CaF_2 crystals; an external one which functions as a veto. The combination of all these features compensates for the lacking of high energy resolution and makes this technique potentially competitive.

The **third category** comprises calorimetric experiments based on detectors which compensate the low energy resolution with tracking or some form of event-topology capability. There are three samples in this group.

EXO [32] is a TPC of enriched liquid or high pressure gaseous xenon, for the investigation of the isotope ^{136}Xe. The set-up will provide event position and topology. In prospect, the tagging of Ba single ion (2β decay daughter) is foreseen with optical spectroscopy methods. The [Ba^{++} e^+ e^-] final state should be identified through laser fluorescence of the Ba ion [33]. The first step (EXO-200), under completion, consists of 200 kg of enriched liquid xenon and will not use the Ba tagging approach. It is located in the WIPP facility, US. EXO-200 sensitivity to $m_{\beta\beta}$ is anticipated to be 133÷186 meV.

The proved energy resolution is 3.3% FWHM (improved thanks to simultaneous measurement of ionization and light). EXO-200 is in the construction phase and will take data from summer 2010. Further steps foresee source masses in the $1 \div 10$ tons range. In parallel with the EXO-200 development, research and development for Ba ion grabbing and tagging is ongoing.

NEXT [34] is a proposed 100 kg high-pressure gaseous-xenon TPC, to be located in CANFRANC, Spain. The extension to 1 ton is technically possible. Clear two-track signature is achievable, thanks to the use of gaseous rather than liquid Xe. The estimated energy resolution is of the order of 1% FWHM, achieved thanks to the electro luminescence signal associated to the ionization electrons produced by the Double Beta Decay events. The experiment is in the research and development phase. The first prototype NEXT-1 is completed. A mid-scale experiment NEXT-10 (10 kg isotope) is under preparation.

COBRA [28] is a proposed array of ^{116}Cd-enriched CdZnTe semiconductor detectors at room temperature. Nine $\beta\beta$ isotopes are under test in principle, but ^{116}Cd is the only competing candidate. The final aim of the project is to deploy 117 kg of ^{116}Cd with high granularity. Small scale prototypes have been realized at LNGS, Italy. The proved energy resolution is 1.9% FWHM. The project is in research and development phase. Recent results on pixellization shows that the COBRA approach may allow an excellent tracking capability (solid state TPC).

The **fourth category** is represented by set-ups with external source (which necessarily leads to low energy resolution) and sophisticated tracking capability, allowing to reach virtually zero background in the relevant energy region (with the exception of the contribution from the $2\nu\beta\beta$ tail). Three projects belong to this class.

SUPERNEMO [35] is a proposed set-up composed by several modules containing source foils, tracking (drift chamber in Geiger mode) and calorimetric (low Z scintillator) sections. A magnetic field is present for charge sign identification. SUPERNEMO will take advantage from the NEMO3 experience, and will investigate ^{82}Se or ^{150}Nd. A possible configuration foresees 20 modules with 5 kg source for each module, providing 100 kg of isotopes, to be located in the planned extension of LSM. The foreseen energy resolution is 4% FWHM. The project is in an advanced research and development phase: the first module, operating as a demonstrator, is foreseen in 2012.

MOON [36] is a proposed Double Beta Decay experiment consisting of multilayer plastic scintillators interleaved with source foils and tracking sections (PL fibers or MWPC). The isotopes under investigation are ^{100}Mo or ^{82}Se or ^{150}Nd. In the ^{100}Mo version, MOON is also a powerful solar neutrino detector. The MOON-1 prototype has been realized without tracking section (2006). The MOON-2 prototype with tracking section is in progress.

The proved energy resolution is 6.8% FWHM. The final target is to collect 5 y ton. The experiment is presently in an research and development phase. A merging with SuperNEMO is foreseen.

DCBA [37] is based on a momentum analyzer for beta particles consisting of source foils inserted in a drift chamber with magnetic field. The isotopes under investigation will be ^{82}Se or ^{150}Nd. A prototype has been realized, with space resolution of ~0.5 mm and energy resolution 11% FWHM at 1 MeV, implying 6% FWHM at 3 MeV (not enough for a competitive experiment). The final target consists of 10 modules with 84 m^2 source foil per module (126 through 330 kg total mass). The present research and development phase aims at the improvement of the energy resolution.

Two promising searches (SNO+ and SUPERNEMO, but also DCBA) depend critically on the possibility of enriching Nd in ^{150}Nd. A large-scale enrichment set-up is viable through laser isotope separation. This opportunity was extensively studied in France, where a specific project aimed at converting a dismissed facility for uranium to the enrichment of Nd [38], but this operation turned out impossible for extra-scientific reasons. Recently [39], a possibility showed up to enrich Nd with centrifugation, as doable for Ge, Mo, Se, Te, and Cd. This requires, however, to design special centrifuges operating at high temperatures at which a gaseous compound of neodymium is available.

5. Prospects and conclusions

In the discussion of the prospects for $0\nu2\beta$ search, it is important to extract from the list examined above those experimental efforts which are in the construction phase (or at least in an advanced research and development phase), and have an approved location, a well established international collaboration and a reliable financial support. If this selection is made, very few projects seem to be now in the position to impact substantially in the future of $0\nu2\beta$ decay search: CUORE, GERDA, EXO-200, SNO+, SUPERNEMO, LUCIFER and possibly NEXT, if the research and development phase confirms the expectation. However, it is not possible to exclude rapid developments of the present research and development programs towards real experiments. The continuation of the research and development activity is crucial, since the future of the search depends critically on the richness and variety of the technologies under development, which can lead to further increases of the sensitivities and to the possibility to study many isotopes with different approaches, essential elements in the medium — long term prospects for $0\nu2\beta$ decay.

The future scenario of Double Beta Decay depends on the choice made by Nature on the neutrino mass pattern.

5.1. Quasi degenerate neutrino mass pattern

In the case of QD pattern, *i.e.* $m_{\beta\beta}$ in the range $100 \div 500$ meV (this would be in agreement with the ^{76}Ge claim), we expect the following developments:

- GERDA will detect $0\nu2\beta$ decay in ^{76}Ge, marginally in phase I and with high statistics in phase II.
- CUORE will detect $0\nu2\beta$ in ^{130}Te and would be technically able to proceed to multi-isotope searches simultaneously in a second phase (^{130}Te–^{116}Cd–^{100}Mo) thanks to the versatility of the bolometric technique if large scale enrichment is funded.
- EXO-200 will detect $0\nu2\beta$ decay in ^{136}Xe.
- SNO+ will detect $0\nu2\beta$ decay in ^{150}Nd.
- LUCIFER could detect $0\nu2\beta$ decay in ^{82}Se if the present research and development phase leads to a significant pilot experiment.
- SUPERNEMO may investigate the mechanism looking at the single electron energy spectrum and at the electron angular distribution in ^{82}Se or in ^{150}Nd.

The redundancy of the candidates with positive observation will help in reducing the uncertainties coming from nuclear matrix element calculation: we would enter the precision measurement era for $0\nu2\beta$ decay!

5.2. Inverted hierarchy neutrino mass pattern

In the case of IH pattern, *i.e.* $m_{\beta\beta}$ in the range $15 \div 50$ meV, detection is still possible in the middle term, under the condition that the projects under development achieve the planned sensitivity in their "aggressive" version:

- CUORE could detect $0\nu2\beta$ decay, more likely if enriched in ^{130}Te or if upgraded in LUCIFER mode.
- SUPERNEMO could marginally detect it in ^{82}Se or ^{150}Nd (if Nd enrichment is viable).
- SNO+ could detect it in ^{150}Nd (if Nd enrichment is viable).
- GERDA phase III, after merging with MAJORANA, could detect it in ^{76}Ge.

The discovery in 3 or 4 isotopes is necessary for a convincing evidence, and it is still possible thanks to the variety of projects and techniques under development.

5.3. Directed hierarchy neutrino mass pattern

In the case of DH pattern, *i.e.* $m_{\beta\beta}$ in the range $2 \div 5$ meV, new strategies have to be developed. Just to give an idea of the size of the difficulty, in this range we expect something like $1 \div 10$ counts in 5 years for several tens of tons of isotopes. That means that the most sensitive searches planned today should be expanded by about a factor 100, in 0 background condition! At the moment, no viable solution is conceivable. However, given the importance of the subject, the brains of the experimental physicists are at work, and the running research and development searches are very important to stimulate new ideas in view of this extreme challenge.

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