NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENTS*

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The study of neutrinoless double beta decay is of outmost importance for neutrino physics. It is considered to be the gold plated channel to probe the fundamental character of neutrinos and to determine the neutrino mass. From the experimental point about nine different isotopes are explored for the search. After a general introduction follows a short discussion on nuclear matrix element calculations and supportive measurements. The current experimental status of double beta searches is presented followed by a short discussion of the ideas and proposals for large scale experiments.

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1. Introduction

Neutrino physics has gone through a revolution in the last ten years. Now it is beyond doubt that neutrinos have a non-vanishing rest mass. All the evidence stems from neutrino oscillation experiments, proving that neutrinos can change their flavour if travelling from a source to a detector. Oscillations violate the concept of single lepton number conservation but total lepton number is still conserved. Furthermore, the oscillation experiments are not able to measure absolute neutrino masses, because their results depend only on the differences of masses-squared, $\Delta m^2 = m_i^2 - m_j^2$, with m_i, m_j as the masses of two neutrino mass eigenstates. In the full three neutrino mixing framework the weak eigenstates ν_e, ν_μ and ν_τ can be expressed as superpositions of three neutrino mass eigenstates ν_1, ν_2 and ν_3 linked via a unitary matrix U:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \qquad (1)$$

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This kind of mixing has been known in the quark sector for decades and the analogous matrix U is called Cabbibo–Kobayashi–Maskawa matrix. The corresponding mixing matrix in the lepton sector is named Pontecorvo–Maki–Nakagawa–Sato (PMNS) matrix. The unitary matrix U in Eq. (1) can be parametrised in the following form

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (2)$$

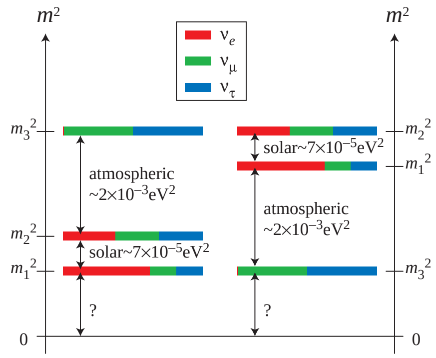
where $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$ $(i,j = 1,2,3)$. The phase δ is a source for CP violation and like in the quark sector cannot be removed by rephasing the neutrino fields. The Majorana case, *i.e.* the requirement of particle and antiparticle to be identical, restricts the freedom to redefine the fundamental fields even further. The net effect is the appearance of a CP-violating phase already in two flavours. For three flavours two additional phases have to be introduced resulting in a mixing matrix of the form

$$U = U_{\mathrm{PMNS}}\ \mathrm{diag}(1, e^{i\alpha_2}, e^{i\alpha_3})\,, \quad (3)$$

with the two new Majorana phases α_2 and α_3. These phases again might only be accessible in double beta decay, they are not accessible in neutrino oscillation experiments. They are a further source of CP violation.

Based on the observations from neutrino oscillations (see [1,2]), various neutrino mass models have been proposed. These can be categorised as normal hierarchy ($m_3 \gg m_2 \approx m_1$), inverted hierarchy ($m_2 \approx m_1 \gg m_3$) and almost degenerate ($m_3 \approx m_2 \approx m_1$) neutrinos (Fig. 1). A key result, based on the observed Δm^2 in atmospheric neutrinos, is the existence of a neutrino mass eigenstate in the region around 10–50 meV. This is the minimal value necessary, because it corresponds to the square root of the measured Δm^2 in case one of the mass eigenstates is zero. Fixing the absolute mass scale is of outmost importance, because it will fix the mixing matrix and various other important quantities will then be determined, like the contribution of neutrinos to the mass density in the Universe.

Traditionally, laboratory experiments search for a finite neutrino rest mass by exploring the endpoint energy of the electron spectrum in tritium beta decay. Currently a limit for the electron neutrino mass of less than 2.2 eV has been achieved [4,5]. A similar limit is obtained by analysing recent cosmic microwave background measurements using the WMAP satellite combined with large scale galaxy surveys and Lyman-α systems, see *e.g.* [6]. However, there are about two orders of magnitude difference with respect to the region below 50 meV and even the next generation beta decay experiment, called KATRIN, can at best lead to an improvement of a factor ten.



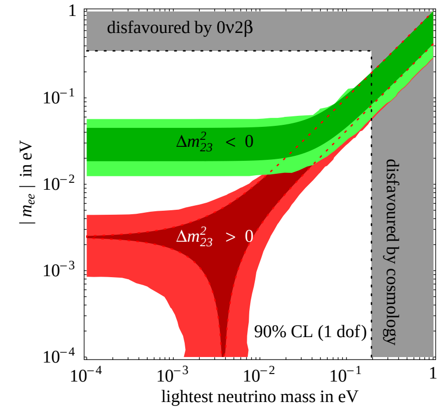


Fig. 1. Left-hand side: Possible configurations of neutrino mass states as suggested by oscillations. Currently a normal (left) and an inverted (right) hierarchy cannot be distinguished. The flavour composition is shown as well. Right-hand side: The effective Majorana mass $\langle m_{\nu_e} \rangle$ as a function of the lightest mass eigenstate m_1. Hierarchical mass patterns can be distinguished for $\langle m_{\nu_e} \rangle$ smaller than 50 meV, otherwise neutrinos can be considered as almost degenerate. Also shown in grey are the regions disfavoured by current $0\nu\beta\beta$-decay limits and a very optimistic limit (could be worse by an order of magnitude) from cosmology (from [3]).

However, it should be noticed, that beta decay and double beta decay are measuring slightly different observables and are rather complementary than competitive. Therefore, very likely double beta decay is the only way to explore the region below 100 meV.

2. Double beta decay

Double beta decay is characterised by a nuclear process changing the nuclear charge Z by two units while leaving the atomic mass A unchanged. It is a transition among isobaric isotopes. It is, therefore, a higher order process and can be seen as two simultaneous beta decays. This can only happen for even–even nuclei. All even–even nuclei have a ground state of spin 0 and a positive parity, hence the ground state transitions are characterised as $(0^+ \rightarrow 0^+)$ transitions. Thus, a necessary requirement for double beta decay to occur is $m(Z,A) > m(Z+2,A)$ and for practical purposes β-decay has to be forbidden $m(Z,A) < m(Z+1,A)$ or at least strongly suppressed. The same ground state configurations and arguments might hold for isotopes on the right side of the even–even parabola. This would lead to the process of double positron decay or double electron capture, discussed later. In nature 35 isotopes are known, which show the specific ground state configuration, necessary for double beta decay. Double beta decay was first discussed by Goeppert-Mayer [7] in the form of

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e\,, \quad (2\nu\beta\beta\text{-decay})\,. \tag{4}$$

This process can be seen as two simultaneous neutron decays (Fig. 2). Shortly after the classical papers of Majorana [8] discussing a 2-component neutrino, Racah [9] and Furry discussed another decay mode in form of [10]

$$(Z,A) \rightarrow (Z+2,A) + 2e^-, \quad (0\nu\beta\beta\text{-decay})\,. \tag{5}$$

In contrast to neutrino oscillations which violate individual flavour lepton number, but keep total lepton number conserved, $0\nu\beta\beta$-decay violates total lepton number by two units. This process is forbidden in the Standard Model. It can be seen as two subsequent steps ("Racah-sequence") as shown in Fig. 2:

$$\begin{aligned} (Z,A) &\rightarrow (Z+1,A) + e^- + \bar{\nu}_e\,, \\ (Z+1,A) + \nu_e &\rightarrow (Z+2,A) + e^-. \end{aligned} \tag{6}$$

First a neutron decays under the emission of a right-handed $\bar{\nu}_e$. This has to be absorbed at the second vertex as a left-handed ν_e. To fulfill these conditions neutrino and antineutrino have to be identical, requiring that neutrinos are Majorana particles, *i.e.* a 2-component object. This is different from all the other fundamental fermions where particles and antiparticles can be already distinguished by their charge. Majorana neutrinos are preferred by most Grand Unified Theories to explain the small magnitude of neutrino masses via the see-saw mechanism. Hence, double beta decay is generally considered to be the "gold plated" channel to probe the fundamental character of neutrinos. Moreover, to allow for the helicity matching a neutrino mass is required. The reason is that the wave-function describing neutrino

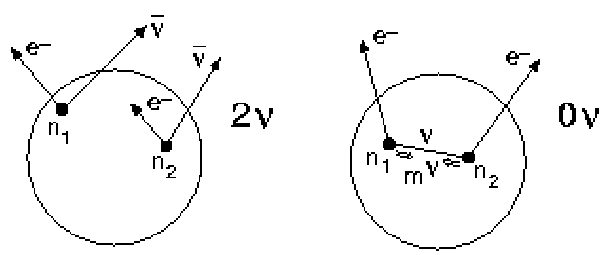


Fig. 2. Principle of double beta decay. Left-hand side: The simultaneous decay of two neutrons as an allowed higher order process ($2\nu\beta\beta$-decay). Right-hand side: The lepton-number violating mode ($0\nu\beta\beta$-decay) where the neutrino only occurs as a virtual particle. This process is not allowed in the Standard Model.

mass eigenstates for $m_\nu > 0$ has no fixed helicity and, therefore, besides the dominant left-handed contribution, has an admixture of a right-handed component (or *vice versa* for antineutrinos), which is proportional to m_ν/E. Thus, for double beta decay to occur, massive Majorana particles are required. For recent reviews on double beta decay see [11–13]. The quantity measured in $0\nu\beta\beta$-decay is called effective Majorana neutrino mass and given for light neutrinos by

$$\langle m_{\nu_e} \rangle = \left| \sum_i U_{ei}^2 m_i \right| = \left| \sum_i \mid U_{ei} \mid^2 e^{2i\alpha_i} m_i \right| , \tag{7}$$

which can be written in case of CP invariance as

$$\langle m_{\nu_e} \rangle = \mid m_1 \mid U_{e1}^2 \mid \pm m_2 \mid U_{e2}^2 \mid \pm m_3 \mid U_{e3}^2 \mid\mid . \tag{8}$$

As can be seen, the different terms in the sum have a chance to interfere destructively, only the absolute value is measured at the end. On the other hand, beta decay measures

$$m_{\bar{\nu}_e} = \sum_i \mid U_{ei}^2 \mid m_i , \tag{9}$$

which is independent of the fundamental character of the neutrino and does not allow destructive interference. As a result, a certain care should be taken if comparing neutrino masses obtained by β-decay and $0\nu\beta\beta$-decay, they should be seen as complementary measurements.

3. General considerations

Being a nuclear decay, the actual experimental quantity measured is the half-life. As a higher order effect the expected half-lives for double beta decay are long, in the region of about 10^{20} years and beyond. The experimental signal of $0\nu\beta\beta$-decay is two electrons in the final state, whose energies add up to the Q-value of the nuclear transition, while for the $2\nu\beta\beta$-decay the sum energy spectrum of both electrons will be continuous (Fig. 3). The total decay rates, and hence the inverse half-lives, are a strong function of the available Q-value. The rate of $0\nu\beta\beta$-decay scales with Q^5 compared to a Q^{11}-dependence for $2\nu\beta\beta$-decay. Therefore, isotopes with a high Q-value (above about 2 MeV) are normally considered for experiments. This restricts one to eleven candidates listed in Table I. The measured half-life or its lower limit in case of non-observation of the process can be converted into a neutrino mass or an upper limit via

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left(\frac{\langle m_{\nu_e} \rangle}{m_e} \right)^2 , \tag{10}$$

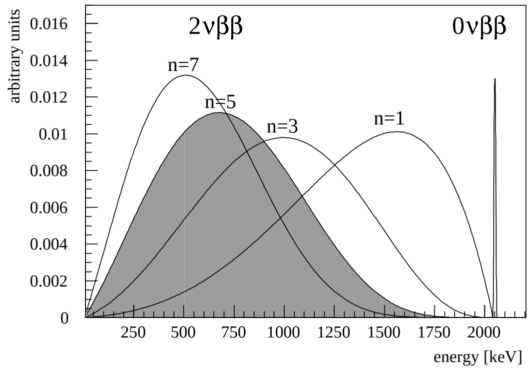


Fig. 3. Schematic drawing of the sum energy spectrum of electrons in double beta decay, here in case of ^{76}Ge. The $2\nu\beta\beta$-decay shows a continuous spectrum (gray), while $0\nu\beta\beta$-decay is a peak at the Q-value of the transition. The additional curves shown correspond to various majoron emitting modes not discussed here.

where $G^{0\nu}$ is the exactly calculable phase space integral (see [14] for numerical values) of the decay and $\mid M^{0\nu} \mid$ is the nuclear matrix element of the transition.

TABLE I

Compilation of $\beta^-\beta^-$-emitters with a Q-value of at least 2 MeV. Shown are the transition energies Q and the natural abundances.

Transition	Q-value (keV)	nat. ab. (%)
$^{48}_{20}$Ca→$^{48}_{22}$Ti	4271	0.187
$^{76}_{32}$Ge→$^{76}_{34}$Se	2039	7.8
$^{82}_{34}$Se→$^{82}_{36}$Kr	2995	9.2
$^{96}_{40}$Zr→$^{96}_{42}$Mo	3350	2.8
$^{100}_{42}$Mo→$^{100}_{44}$Ru	3034	9.6
$^{110}_{46}$Pd→$^{110}_{48}$Cd	2013	11.8
$^{116}_{48}$Cd→$^{116}_{50}$Sn	2809	7.5
$^{124}_{50}$Sn→$^{124}_{52}$Te	2288	5.64
$^{130}_{52}$Te→$^{130}_{54}$Xe	2530	34.5
$^{136}_{54}$Xe→$^{136}_{56}$Ba	2479	8.9
$^{150}_{60}$Nd→$^{150}_{62}$Sm	3367	5.6

With reasonable assumptions on the nuclear matrix element it can be estimated that for a neutrino mass measurement of the order of 50 meV, half-lives in the region of 10^{26}–10^{27} years must be explored, by no means an easy task. This can be shown by the following estimate: assume the radioactive decay law in the approximation $T_{1/2} \gg t$

$$T_{1/2}^{0\nu} = \ln 2 a N_{\mathrm{A}} m \frac{t}{N_{\beta\beta}}\,, \tag{11}$$

with t the measuring time, m the used mass, a is the natural abundance of the isotope of interest, N_{A} the Avogadro constant and $N_{\beta\beta}$ the number of double beta decays. Expecting a half-life of about 6×10^{26} yrs and to observe as little as one decay per year, the number of source atoms required is around 6×10^{26}. This, however, corresponds to 1000 moles and using an average isotope of mass 100 like ^{100}Mo, would immediately imply using about 100 kg. Hence, even without any disturbing background, and full efficiency for detection, one needs about hundred kilogram of the isotope of interest, to observe one decay per year independent of the experimental approach! Even worse, in the background-limited case, the sensitivity on the half-life depends on experimental quantities according to

$$T_{1/2}^{0\nu} \propto a\,\varepsilon \sqrt{\frac{M\,t}{\Delta E\,B}}\,, \tag{12}$$

with a the natural abundance of the isotope of interest, ε the detection efficiency, M the mass of source employed, t the measuring time, ΔE the energy resolution at the peak position and B the background index, typically quoted in events/yr/keV/kg. In contrast to the background-free case, for a background-limited experiment the half-life sensitivity increases only with the square root of the measuring time and mass.

3.1. Nuclear matrix elements

As can be seen in Eq. (10) major ingredients in the conversion of measured half-lives into neutrino masses are the involved nuclear matrix elements. Those calculations are performed within the quasi random phase approximation (QRPA) or by using the shell model. While $2\nu\beta\beta$-decay matrix element are pure Gamow–Teller transitions as only 1^+-states in the intermediate nucleus are contributing, in $0\nu\beta\beta$-decay also higher multipoles contribute. A detailed discussion is beyond this article, for details see [15–18]. There still seems to be an uncertainty of a factor 2–3 in the calculations, the treatment of short range-correlation functions are likely responsible for a significant part of the discrepancy. Hence, an initiative has recently been started to provide those calculations with more and better input from the experimental side to help as much as possible to settle the issue [19]. Those measurements include charge exchange reactions measuring the transition strengths to 1^+-states. Some of the isotopes have already been measured at KVI Groningen with the $(d,{}^2\mathrm{He})$ reactions complemented by $({}^3\mathrm{He},t)$ measurements performed at RCNP Osaka (Fig. 4). New ft-value measurements of electron capture for the intermediate nuclei are proposed using atomic traps [21]. Those might help to solve the issue of how to fix the particle–particle coupling parameter g_{pp}, to which the 1^+ states calculations are very sensitive. Atomic traps will be of usage as well to determine the Q-values of some transitions more accurately by high precision mass spectrometry. In addition, ordinary muon capture and neutrino–nucleus scattering have been proposed to gain further information on the involved matrix elements. The hope is that all those measurements might allow to bring down the error to the level of 30 %.

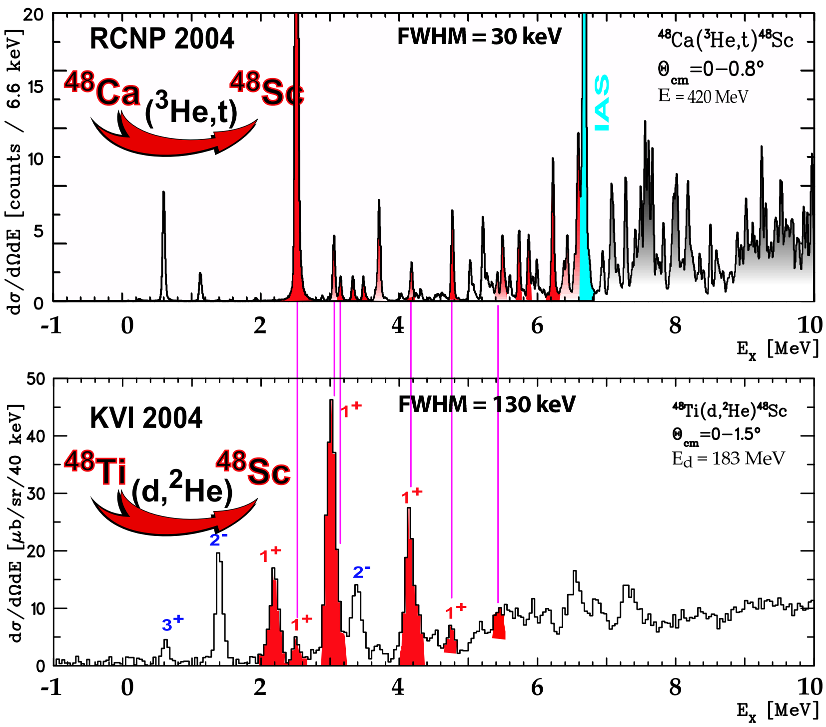


Fig. 4. Measured ${}^{48}\mathrm{Ca}({}^3\mathrm{He},t){}^{48}\mathrm{Sc}$ (RCNP Osaka) and ${}^{48}\mathrm{Ti}(d,{}^2\mathrm{He}){}^{48}\mathrm{Sc}$ (KVI Groningen) spectra in charge exchange reactions at 0 degree. Intermediate states which are excited by both reactions are on top of each other (from [20]).

4. Experimental status

The search for $0\nu\beta\beta$-decay relies on finding a peak in the region below 4.3 MeV, depending on the isotope (see Table I). Common to all experimental approaches is the aim for a very low-background environment due to the fact of the expected long half-lives. Among the most common background sources are the natural decay chains of U and Th, ^{40}K, Rn, neutrons, atmospheric muons and radio-isotopes produced in materials while on the surface.

All direct experiments are focusing on electron detection and can be either active or passive. Active detectors are such that source and detector are identical which is a big advantage, but often only measure the sum energy of both electrons. On the other hand, passive detectors (source and detector are different) allow to get more information like measuring energy and tracks of both electrons separately, but usually have smaller source strength. Some experiments will be described now in a little more detail.

4.1. Ge-semiconductors — Heidelberg–Moscow and IGEX

The major progress in the last decades pushing half-life limits and increase the sensitivity towards smaller and smaller neutrino masses have been achieved using Ge-semiconductor devices. Source and detector are identical, the isotope under investigation is ^{76}Ge having a Q-value of 2039 keV. The big advantage is the excellent energy resolution of Ge-semiconductors (typically about 3–4 keV at 2 MeV). However, the technique only allows the measurement of the sum energy of the two electrons. A big step forward due to an increase in source strength was done by using enriched germanium (the natural abundance of ^{76}Ge is 7.8 %). Two experiments were performed recently, the Heidelberg–Moscow and the IGEX experiment. The Heidelberg–Moscow experiment in the Gran Sasso Laboratory took data from 1990–2003 using 11 kg of Ge enriched to about 86 (HPGe). A background as low as 0.12 counts/yr/kg/keV at the peak position has been achieved. After 53.9 kg × yr of data taking the peak region reveals no signal and the obtained half-life limit is [22] $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yrs (90 % CL) which can be converted using Eq. (12) and the matrix elements given in [23] to an upper bound of $\langle m_{\nu_e} \rangle < 0.35$ eV. This is currently the best available bound coming from double beta decay. However, recently a subgroup of the collaboration found a small peak at the expected position [24, 29] (Fig. 5). Taking the peak as real and based on 71.7 kg× yr of data would point towards a half-life between 0.7–4.2 $\times 10^{25}$ yrs. Using the matrix elements calculated in [23] this would imply a range for the neutrino mass between 0.2–0.6 eV, which might be widened by using other matrix element calculations. If true, this would immediately result in the fact that neutrinos are almost degenerate. However, the discussion concerning the possible evidence is still quite controversial, see [3, 25–28].

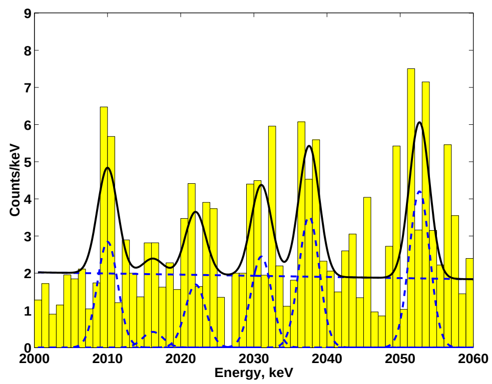


Fig. 5. Energy spectrum of the Heidelberg–Moscow experiment around the $0\nu\beta\beta$-decay region at 2040 keV (from [29]).

4.2. CdZnTe-semiconductors — COBRA

A new approach to take advantage of the good energy resolution of semiconductors is COBRA [30] located in the Gran Sasso Underground Laboratory (LNGS). In total, there are seven (nine in case of CdZnTe) double beta emitters within the detector including those of $\beta^+\beta^+$ decay. The idea here is to use CdZnTe detectors, mainly to explore ^{116}Cd and ^{130}Te decay and ^{106}Cd for $\beta^+\beta^+$ decay. The smallness of the detectors makes a search for coincidences powerful and reduces γ-background. The practical handling is simplified as these detectors are room temperature detectors. In case of pixelated detectors it offers tracking possibilities and even further background reduction. Recent results obtained with four detectors can be found in [31]. Currently an upgrade to 64 detectors is ongoing, corresponding to about 0.42 kg CdZnTe (Fig. 6).

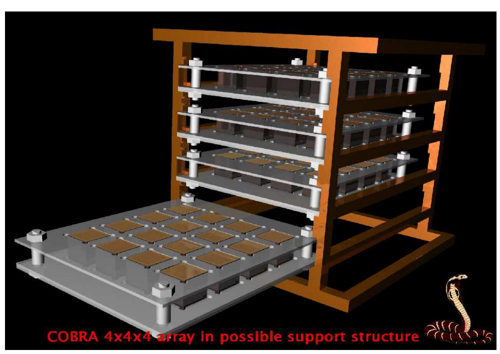


Fig. 6. Schematic layout of the COBRA 64 array in form of a $4\times4\times4$ configuration. Each layer contains 16 CdZnTe semiconductor detectors.

4.3. Cryogenic bolometers — CUORICINO

Currently only two large scale experiments are running. The first technique uses bolometers running at very low temperature (mK). CUORICINO at the Gran Sasso Underground Laboratory in Italy, is operating 62 TeO_2 crystals, corresponding to about 40 kg, at 8 mK to search for the ^{130}Te decay with a Q-value of 2530 keV. The obtained half-life limit corresponds to [32] $T^{0\nu}_{1/2}(^{130}\text{Te}) > 2.2 \times 10^{24}$ yr (90 % CL) resulting in a upper bound on the neutrino mass of 0.2–1.1 eV, depending on the used matrix elements.

4.4. Time projection chambers — NEMO-3

The second experiment, NEMO-3 in the Frejus Underground Laboratory, is of the form of a passive experiment, which is mostly built in form of time projection chambers (TPCs) where the double beta emitter is either the filling gas of the chamber (like ^{136}Xe) or is included in thin foils. The advantage is that energy measurements as well as tracking of the two electrons is possible. Disadvantages are the energy resolution and in case of using thin foils the limited source strength. NEMO-3 consists of a tracking (wire chambers) and a calorimetric (plastic scintillators) device put into a 25 G magnetic field. The total source strength is about 10 kg which in a first run is dominated by using enriched ^{100}Mo foils (about 7 kg). Limits of $T^{0\nu}_{1/2}(^{100}\text{Mo}) > 5.6 \times 10^{23}$ yr (90 % CL) and $T^{0\nu}_{1/2}(^{82}\text{Se}) > 2.7 \times 10^{23}$ yr

TABLE II

Compilation of some obtained limits for $0\nu\beta\beta$-decay. However, notice the claimed evidence for ^{76}Ge. All results are 90 % CL, except ^{48}Ca (76 %) and ^{128}Te (68 %).

Isotope	Half-life limit (yrs)	ν mass limit (eV)
$^{48}_{20}\text{Ca}\rightarrow^{48}_{22}\text{Ti}$	$> 9.5 \times 10^{21}$ (76%)	< 8.3
$^{76}_{32}\text{Ge}\rightarrow^{76}_{34}\text{Se}$	$> 1.9 \times 10^{25}$ (90%)	< 0.35
$^{76}_{32}\text{Ge}\rightarrow^{76}_{34}\text{Se}$	$0.7\text{–}4.2 \times 10^{25}$ (90%)	0.2–0.6
$^{82}_{34}\text{Se}\rightarrow^{82}_{36}\text{Kr}$	$> 2.7 \times 10^{23}$ (90%)	< 5.0
$^{100}_{42}\text{Mo}\rightarrow^{100}_{44}\text{Ru}$	$> 5.6 \times 10^{23}$ (90%)	$< 0.6\text{–}2$
$^{116}_{48}\text{Cd}\rightarrow^{116}_{50}\text{Sn}$	$> 1.2 \times 10^{23}$ (90%)	< 2.6
$^{128}_{52}\text{Te}\rightarrow^{128}_{54}\text{Xe}$	$> 7.7 \times 10^{24}$ (68%)	$< 1.1^*$
$^{130}_{52}\text{Te}\rightarrow^{130}_{54}\text{Xe}$	$> 2.2 \times 10^{24}$ (90%)	$< 0.2\text{–}1.1$
$^{136}_{54}\text{Xe}\rightarrow^{136}_{56}\text{Ba}$	$> 4.4 \times 10^{23}$ (90%)	< 2.3
$^{150}_{60}\text{Nd}\rightarrow^{150}_{62}\text{Sm}$	$> 2.1 \times 10^{21}$ (90%)	< 4.1

*corresponds to a geochemical measurement.

(90 % CL) resulting in upper neutrino mass bound of 0.6–2 eV from ^{100}Mo have been achieved [33]. Observation of $2\nu\beta\beta$-decay has been quoted now for about a dozen isotopes. A complete listing of all experimental results obtained until end of 2001 can be found in [34], some newer values are in [13], the most important ones are shown in Table II.

5. Interpretation of the obtained results

It should be noted that double beta decay could also occur through other $\Delta L = 2$ processes besides light Majorana neutrino exchange. Whatever kind of new physics is providing this lepton number violation with two electrons in the final state will be restricted by the obtained experimental results. Among them are right-handed weak interactions, heavy Majorana neutrino exchange, double charged higgs bosons, R-parity violating SUSY couplings, leptoquarks and other Beyond Standard Model physics.

Assume that in addition to the neutrino mass mechanism, also right handed leptonic and hadronic currents can contribute, *i.e.* the existence of a new $(V + A)$ interaction in addition to the well known $(V - A)$ interaction. The general Hamiltonian used for $0\nu\beta\beta$-decay rates is then given by

$$H = \frac{G_{\rm F}\cos\theta_{\rm C}}{\sqrt{2}}(j_{\rm L}J_{\rm L}^\dagger + \kappa j_{\rm L}J_{\rm R}^\dagger + \eta j_{\rm R}J_{\rm L}^\dagger + \lambda j_{\rm R}J_{\rm R}^\dagger)\,, \tag{13}$$

with $G_{\rm F}$ as the Fermi constant, $\cos\theta_{\rm C}$ as the Cabibbo angle and the left- and right-handed leptonic currents given as

$$j_{\rm L}^\mu = \bar{e}\gamma^\mu(1-\gamma_5)\nu_{e{\rm L}}\,, \qquad j_{\rm R}^\mu = \bar{e}\gamma^\mu(1+\gamma_5)\nu_{e{\rm R}}\,, \tag{14}$$

respectively. The coupling constants κ, η, λ vanish in the Standard Model and $\kappa = \eta$ in left–right symmetric theories. Expression 12 can be generalised if right-handed currents are included to

$$\begin{aligned}\left(T_{1/2}^{0\nu}\right)^{-1} &= C_{mm}(\frac{\langle m_{\nu_e}\rangle}{m_e})^2 + C_{\eta\eta}\langle\eta\rangle^2 \\ &\quad + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{m\eta}(\frac{\langle m_{\nu_e}\rangle}{m_e})\langle\eta\rangle \\ &\quad + C_{m\lambda}(\frac{\langle m_{\nu_e}\rangle}{m_e})\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle\,,\end{aligned} \tag{15}$$

where the coefficients C contain the phase space factors and the matrix elements and the effective quantities are

$$\langle\eta\rangle = \eta\sum_j U_{ej}V_{ej}\,, \qquad \langle\lambda\rangle = \lambda\sum_j U_{ej}V_{ej} \tag{16}$$

with V_{ej} as the mixing matrix elements among the right-handed neutrino states. Eq. (15) reduces to Eq. (12) in case $\langle\eta\rangle, \langle\lambda\rangle = 0$. Allowing also right-handed currents to contribute, $\langle m_{\nu_e}\rangle$ is fixed by an ellipsoid. The weakest mass limit allowed occurs for $\langle\lambda\rangle, \langle\eta\rangle \neq 0$. In this case the half-life limit of ^{76}Ge corresponds to limits of $\langle m_{\nu_e}\rangle < 0.56\,eV, \langle\eta\rangle < 6.5\times10^{-9}$ and $\langle\lambda\rangle < 8.2\times10^{-7}$, respectively.

5.1. $\beta^+\beta^+$-decay

There is still more to investigate than the electron emitting double beta decay discussed. One example is the counterpart emitting two positrons. Three different decay channels can be considered for the latter

$$(Z,A) \rightarrow (Z-2,A) + 2e^+ + (2\nu_e)\,, \tag{17}$$
$$e^- + (Z,A) \rightarrow (Z-2,A) + e^+ + (2\nu_e)\,, \tag{18}$$
$$2e^- + (Z,A) \rightarrow (Z-2,A) + (2\nu_e)\,, \tag{19}$$

where the last two cases involve electron capture (EC). Especially the β^+/EC mode shows an enhanced sensitivity to right handed weak currents [35]. The experimental signatures of the decay modes involving positrons in the final state are promising because of two or four 511 keV photons. Despite this nice signature, they are less often discussed in literature, because for each generated positron the available Q-value is reduced by $2m_ec^2$, which leads to much smaller decay rates than in comparable $\nu\beta\beta$-decay. Hence, for $\beta^+\beta^+$-decay to occur, the Q-values must be at least 2048 keV. Only six isotopes are known to have such a high Q-value, see Table III. The full Q-value is only available in the EC/EC mode. Its detection is experimentally more

TABLE III

Compilation of $\beta^+\beta^+$-emitters requiring a Q-value of at least 2048 MeV. Shown are the full transition energies Q-$4m_ec^2$ and the natural abundances.

Transition	Q-$4m_ec^2$ (keV)	nat. ab. (%)
$^{78}_{36}$Kr→$^{78}_{34}$Se	838	0.35
$^{96}_{44}$Ru→$^{96}_{42}$Mo	676	5.5
$^{106}_{48}$Cd→$^{106}_{46}$Pd	738	1.25
$^{124}_{54}$Xe→$^{124}_{52}$Te	822	0.10
$^{130}_{56}$Ba→$^{130}_{54}$Xe	534	0.11
$^{136}_{58}$Ce→$^{136}_{56}$Ba	362	0.19

challenging, basically requiring the concept of source equal to detector again. In the 0ν mode because of energy and momentum conservation additional particles must be emitted like an e^+e^- pair or internal bremsstrahlung photons. There will be a resonance enhancement in the decay rate if the initial and final states are degenerate as has recently been explored in the context of radiative EC/EC [36]. Current half-life limits are of the order of 10^{20} yrs obtained with ^{106}Cd and ^{78}Kr for the modes involving positrons [34]. The ^{106}Cd system is currently explored by TGV2 [37] and COBRA. The COBRA experiment has the chance of simultaneously measuring 5 different isotopes for this decay channels [30]. As the decay is intrinsic to the CdZnTe detectors one has a good chance to observe the 2ν EC/EC and for the positron emitting modes coincidences among the crystals can be used.

6. Future

The future activities are basically driven by three factors:

- Explore the claimed evidence observed for ^{76}Ge.
- Increase sensitivity for neutrino masses down to 50 meV.
- Explore further processes to disentangle the various underlying physics mechanisms discussed for neutrinoless double beta decay and to compensate for the nuclear matrix elements uncertainties.

To address the first topic, experiments have to come up with similar good experimental parameters like the Heidelberg–Moscow experiment, *i.e.* about 10 yrs measuring time, 11 kg of high isotopical abundance (88 %), superb energy resolution and excellent low background in the peak region. Partly those parameters can be compensated by using an isotope with higher Q-value and more favourable matrix elements. As shown in the previous section, CUORICINO and NEMO-3 are starting to restrict the claimed region of neutrino masses. Very likely the next experiment to join is GERDA [38], using the former Heidelberg–Moscow and IGEX Ge-semiconductor detectors. Concerning the second item various ideas and proposals are available which are listed in Table IV. The last item requires the study of other processes like β^+/EC modes, transitions to excited 2^+-states [35, 39] or LFV processes using charged leptons like $\mu \rightarrow e + \gamma$ [40]. Furthermore, to account for the possible physics processes and matrix element uncertainties, the measurement of at least 3–4 different double beta isotopes might be necessary [41].

TABLE IV

Compilation of proposals for future experiments. This table is a slightly modified version of the one given in [13] and does not claim to be complete.

Experiment	Isotope	Experimental approach
CANDLES	48Ca	Several tons of CaF_2 crystals in Liquid scintillator
CARVEL	^{48}Ca	100 kg $^{48}CaWO_4$ crystal scintillators
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, expand to larger masses
GSO	^{160}Gd	2t Gd_2SiO_3:Ce crystal scintillator in liquid scintillator
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses
MOON	^{100}Mo	several tons of Mo sheets between scintillator
SNO++	^{150}Nd	1000 t of Nd-loaded liquid scintillator
SuperNEMO	^{82}Se	100 kg of Se foils between TPCs
Xe	^{136}Xe	1.56 t of Xe in liquid scintillator
XMASS	^{136}Xe	10 t of liquid Xe

7. Summary

While the observed $2\nu\beta\beta$-decay is the rarest processes ever observed, there is an enormous physics potential in the lepton number violating process of $0\nu\beta\beta$-decay. In addition to the standard analysis, assuming the exchange of a light Majorana neutrino, various other kinds of $\Delta L = 2$ can severely be restricted. There is a hotly debated evidence for a signal in agreement with neutrino masses between 0.2–0.6 eV which would imply almost degenerate neutrinos. If this turns out not to be real, the next benchmark number experiments are aiming for, is the 50 meV range, implying hundreds of kilogram of material. After identifying a positive signal, it will be necessary to figure out which lepton number violating physics process is dominating neutrinoless double decay and especially the contribution of light Majorana neutrino exchange. Covering also the nuclear matrix uncertainties it will be necessary to study several isotopes. Various experimental approaches are discussed to accommodate for this. New co-ordinated actions are on their way to provide the nuclear matrix element calculations with better experimental input parameters. Last, but not least, $0\nu\beta\beta$-decay might be the only opportunity to access two further possible CP-violating phases associated with the Majorana character of the neutrino. This might be important in the context of leptogenesis, explaining the observed baryon asymmetry in the Universe with the help of CP violation in the lepton sector.

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