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Double beta decay

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Double beta decay is a rare nuclear process changing the nuclear charge by two units leaving atomic number unchanged. The detection of the neutrino accompanied mode $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$. *with half-lives around* 10^{20} *years is among the rarest decays ever observed. Of outmost importance for particle physics and especially neutrino physics, is the neutrinoless mode* $(A,Z) \rightarrow (A,Z+2) + 2e^-$. *This process is violating lepton number by two units and requires massive Majorana neutrinos, i.e. neutrino and antineutrino are identical. The current experimental status is reviewed and an outlook towards future activities is given.*

1. Introduction

Neutrinos play a fundamental role in various areas of modern physics from particle physics to cosmology. Since their postulation by Wolfgang Pauli in 1930 to explain the continuous energy spectrum of electrons in nuclear beta decay their investigation is closely coupled to our understanding of weak interactions. After their discovery in 1953, but due to a lack of experimental evidence for any mass, neutrinos have been implemented in the very successful Standard Model of Particle Physics as massless particles. This implies a featureless object with rather limited properties.

However, neutrino physics has been through a revolution over about the last ten years. It is now 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 (see [1,2] for more details). Thus the concept of single lepton number conservation, assigning an individual lepton number to each of the three lepton generations (electron, muon, tau-lepton and their associated neutrinos) separately, is violated. However, 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. To be more specific, in the 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:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad (1)$$

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. Experimental evidence for neutrino oscillations comes from solar neutrino studies, especially the Sudbury Neutrino Observatory SNO, which are independently confirmed by observations using nuclear power plants [3,4,5]. These results point towards a $\Delta m_{12}^2 \approx 8 \times 10^{-5} eV^2$. In addition, the study of atmospheric neutrinos, produced in interactions of cosmic rays in the atmosphere, shows a severe zenith angle dependence, i.e. those ν_μ, which have to travel through the Earth before detection are significantly reduced with respect to those produced above the experiment [6]. To explain this fact via the phenomenon of oscillations a $\Delta m_{23}^2 \approx 2.5 \times 10^{-3} eV^2$ is required. It should be mentioned, that there is further evidence not yet confirmed by other experiments coming from accelerator searches [7,8,9], which do not fit the parameters mentioned above, and should be, for the sake of simplicity, ignored in the following discussion. Based on the observations, various neutrino mass models have been proposed. These can be

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categorized 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 (figure 1). A key result, based on the observed Δm^2, 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 various 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 [10]. 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 [11,12]. 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 of ten. Therefore, double beta decay is very likely the only way to explore the region below.

2. Double beta decay

Double beta decay is characterized as 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. For a specific atomic number the masses around the stable isotope can be approximated by a parabola as shown in figure 2. Isotopes from the left side decay via β^--decay and isotopes on the right via β^+-decay and electron capture. However, in the case of odd-odd and even-even nuclei, those with an odd (even) number of neutrons and odd (even) number of protons an additional term shows up, the nuclear pairing energy, with same magnitude but, opposite sign. This leads to a splitting of the mass parabola into two. Now a special situation among the ground states of nuclei can occur. Certain nuclei would have a chance to decay into the second nearest neighbour, if two subsequent beta decays via an intermediate state could happen. This process is called double beta decay. It is therefore a higher order process and can be seen as two simultaneous beta decays. This can only happen for isotopes on the lower parabola, which is the one containing 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 M. Goeppert-Mayer [13] in the form of

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

This process can be seen as two simultaneous neutron decays (figure 3). Shortly after the classical papers of Majorana [14] discussing a 2-component neutrino, and Racah [15], Furry discussed another decay mode in the form of [16]

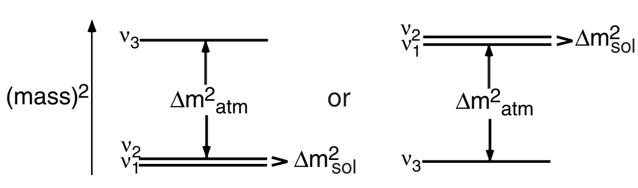

Figure 1. The two kinds of neutrino mass models. Left, the normal hierarchy, where the big gap is determined by atmospheric neutrino data and the finer splitting is given by solar data. Right, the inverted scheme. Here the solar neutrino splitting is in the upper pair of states. In addition, there exists the almost degenerate scenario, where all neutrinos have more or less the same mass, and the small differences are determined by atmospheric and solar oscillation data.

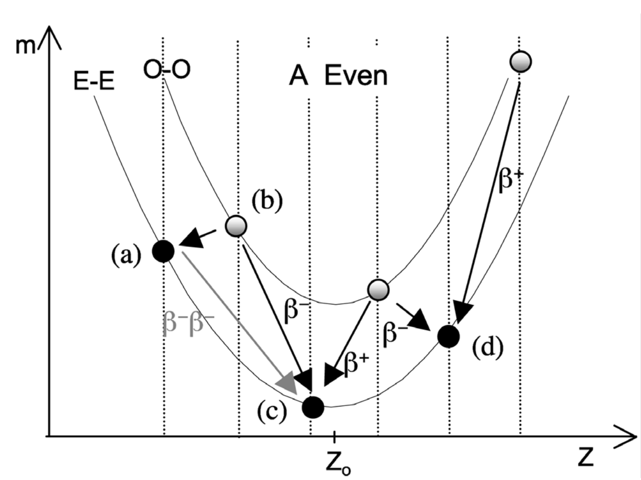

Figure 2. Ground state mass parabola for isobaric nuclei, showing the necessary configuration for double beta decay. Only the one (a) on the even-even (E-E) shell, whose β-decay is blocked (b) but which could decay via two subsequent steps (c) is allowed to do double beta decay. The shift of the parabola of the odd-odd (O-O) nuclei is due to the nuclear pairing energy.

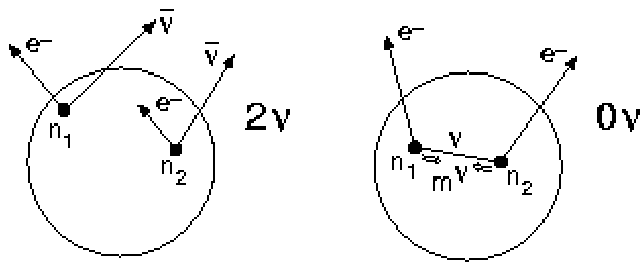

Figure 3. Principle of double beta decay. Left, the simultaneous decay of two neutrons as an allowed higher order process ($2\nu\beta\beta$-decay). Right, the lepton-number violating mode ($0\nu\beta\beta$-decay) where the neutrino only occurs as a virtual particle. This process is not allowed in the Standard Model.

$$(Z, A) \rightarrow (Z+2, A) + 2e^-. \quad (0\nu\beta\beta - \text{decay}) \tag{3}$$

In contrast to neutrino oscillations which violate 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 figure 3:

$$\begin{aligned}(Z, A) &\rightarrow (Z+1, A) + e^- + \bar{\nu}_e \\ (Z+1, A) + \nu_e &\rightarrow (Z+2, A) + e^-.\end{aligned} \tag{4}$$

First a neutron decays under the emission of a right-handed $\bar{\nu}_e$. It 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 neutrinos to be 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. 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 wavefunction describing neutrino 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 neutrinoless double beta decay to occur, massive Majorana particles are required.

2.1. *Beta decay versus double beta decay*

Despite the close relation between the processes themselves, there are profound differences between the actual measured quantities. The first one is the sensitivity to the fundamental character of the neutrino. While $0\nu\beta\beta$-decay can only occur if neutrinos are Majorana particles, β-decay is insensitive to the character and can occur in both the Dirac and Majorana case. Hence, any obtained mass limit in beta decay applies to all neutrinos, while $0\nu\beta\beta$-decay bounds are restricted to Majorana particles. The second important feature is the actual measured quantity. As mentioned, β-decay measures the electron energy spectrum close to the Q-value of the transition and searches for an offset due to the finite rest mass of the neutrino $m_\nu c^2$. The Q-value corresponds to the released energy in the nuclear transition. In the case of a mixing of neutrinos as described by equation (1) the different components lead to an offset of $Q - m_i c^2$ with $i = 1, 2, 3$, which in principle leads to kinks in the beta spectrum. However, if the neutrino mass eigenstates are too close together to be resolved, the measurements result in a superposition of all three mass states weighted by the corresponding matrix elements

$$m_{\bar{\nu}_e} = \sum_i |U_{ei}^2| m_i. \tag{5}$$

The case is more complex for $0\nu\beta\beta$-decay. As in the quark sector, the unitary matrix U in equation (1) can be parametrised in the following form

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{6}$$

where $s_{ij} = \sin\theta_{ij}$, and $c_{ij} = \cos\theta_{ij}$ $(i, j = 1,2,3)$. The phase δ is a source for CP-violation and like in the quark sector cannot be removed by rephasing the neutrino fields. In the Majorana case, 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

$$U = U_{PMNS} diag(1, e^{i\alpha_2}, e^{i\alpha_3}), \tag{7}$$

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. Hence, the quantity measured in $0\nu\beta\beta$-decay is called effective Majorana neutrino mass and given for light neutrinos by

$$\langle m_{\nu_e} \rangle = |\sum_i U_{ei}^2 m_i| = |\sum_i |U_{ei}|^2 \, e^{2i\alpha_i} m_i|. \tag{8}$$

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. However, double beta decay again might be a unique way to observe the two new complex phases associated with the Majorana character. 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 rather be seen as complementary measurements.

3. Sensitivity

Being a nuclear decay, the actual experimental quantity measured is the half-life. However, because double beta decay is a higher order effect the expected half-lives 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 (figure 4). 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 with a Q^{11}-dependence for $2\nu\beta\beta$-decay coming from phase space integration. Therefore isotopes with a high Q-value (above about 2 MeV) are normally considered for experiments. This restricts one to 11 candidates listed in table 1. 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

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M^{0\nu}|^2 \left(\frac{\langle m_{\nu_e}\rangle}{m_e}\right)^2, \qquad (9)$$

where $G^{0\nu}$ is the exactly calculable phase space integral (see [17] for numerical values) of the decay and $|M^{0\nu}|$ is the nuclear matrix element of the transition.

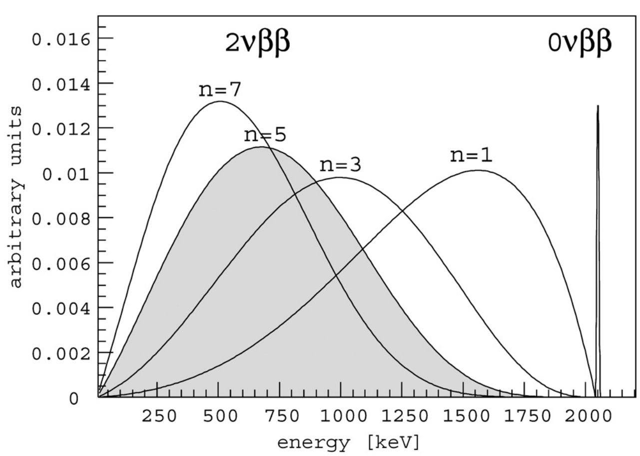

Figure 4. Schematic drawing of the sum energy spectrum of electrons in double beta decay, here in the case of ^{76}Ge. The $2\nu\beta\beta$-decay shows a continuous spectrum (grey), while $0\nu\beta\beta$-decay is a peak at the Q-value of the transition. The additional curves shown correspond to various Majoron emitting modes, discussed later.

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 rough estimate: assume the radioactive decay law in the approximation $T_{1/2} \gg t$

$$T_{1/2}^{0\nu} = \ln 2 a N_A m t / N_{\beta\beta}, \qquad (10)$$

with t being 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} years 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, would immediately imply 100 kg. Hence, even without any disturbing background, and full efficiency for detection, one needs about hundred kilograms of the isotope of interest, to observe one decay per year! Even worse, in the background-limited case, the sensitivity on the half-life depends on experimental quantities according to

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}, \qquad (11)$$

with a being the natural abundance of the isotope of interest, ε the detection efficiency, M the mass of the source employed, t the measurement time, ΔE the energy resolution at the peak position and B the background index, typically quoted in events/year/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.

Table 1. Compilation of $\beta^-\beta^-$ -emitters with a Q-value of at least 2 MeV. The transition energies Q and the natural abundances are shown.

Transition	Q-value (keV)	nat. ab. (%)
$^{48}_{20}Ca \rightarrow ^{48}_{22}Ti$	4271	0.187
$^{76}_{32}Ge \rightarrow ^{76}_{34}Se$	2039	7.8
$^{82}_{34}Se \rightarrow ^{82}_{36}Kr$	2995	9.2
$^{96}_{40}Zr \rightarrow ^{96}_{42}Mo$	3350	2.8
$^{100}_{42}Mo \rightarrow ^{100}_{44}Ru$	3034	9.6
$^{110}_{46}Pd \rightarrow ^{110}_{48}Cd$	2013	11.8
$^{116}_{48}Cd \rightarrow ^{116}_{50}Sn$	2802	7.5
$^{124}_{50}Sn \rightarrow ^{124}_{52}Te$	2288	5.64
$^{130}_{52}Te \rightarrow ^{130}_{54}Xe$	2533	34.5
$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba$	2479	8.9
$^{150}_{60}Nd \rightarrow ^{150}_{62}Sm$	3367	5.6

4. Nuclear matrix elements

The main uncertainty in extracting a bound or a value on $\langle m_{\nu_e} \rangle$ comes from the nuclear matrix element involved in equation (9). They must be calculated by theory. Two basic approaches are followed in the calculations, either the nuclear shell model approach or the quasi random phase approximation (QRPA). All calculations are quite complex and beyond the scope of this article. Detailed treatments can be found in [17–22].

Different situations are associated with the various decay modes. In $2\nu\beta\beta$-decay four spin 1/2 particles are emitted. Isospin, spin and parity selection rules require this decay to occur only via intermediate 1^+ states, called Gamow-Teller (GT) transitions (figure 5). $0\nu\beta\beta$-decay with exchange of light Majorana neutrinos does not have such selection rules on the angular momentum and parity quantum numbers, therefore also contributions from Fermi transitions. Hence, to determine the decay rate, all transition probabilities including their signs have to be calculated. Various approaches have been tried, with QRPA as the most common and shell model calculations only being available for the lightest nuclei. A compilation is given in [23]. The $2\nu\beta\beta$-decay calculations depend sensitively on a single free parameter, called g_{pp}, which has to be determined from experiment. QRPA and its various extensions are typically able to explain the experimental values by adjusting this one parameter g_{pp}, which might differ from isotope to isotope. It is also suggested by computer simulations [24] that a few low lying states account for the whole matrix element, i.e. it might be sufficient to describe correctly the β^+ and β^- amplitudes of low-lying states. In the extreme a single transition dominates the whole transition probability ('single state dominance'). In recent years nuclear shell model methods have become capable of handling much larger configuration spaces than before and can be used for descriptions as well, but are still restricted to rather light nuclei.

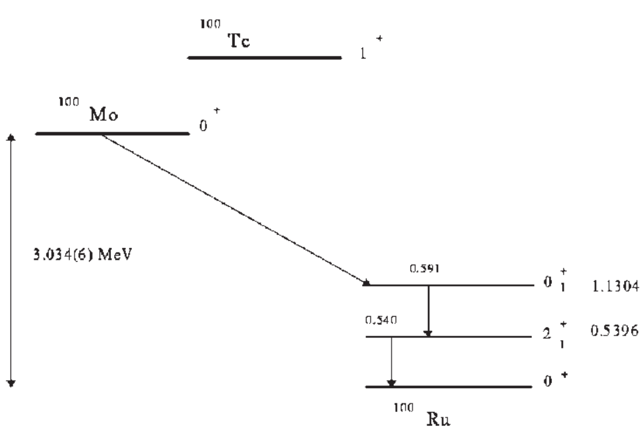

Figure 5. Transitions in double beta decay shown for ^{100}Mo. In addition to ground state transitions also transitions into excited 0^+ and 2^+ states are possible. The decay process occurs by two subsequent Gamow-Teller transitions via the intermediate 1^+ ground state of ^{100}Tc. Also excited states of ^{100}Tc (not shown) contribute to the transition matrix element.

In the case of $0\nu\beta\beta$-decay mediated by light virtual Majorana neutrinos several new features arise. According to the Heisenberg's uncertainty relation the virtual neutrino can have a momentum up to $q \simeq 1/r_{nn} \simeq 50 - 100\ MeV$ where r_{nn} is the distance between the decaying nucleons. Therefore, the dependence on the energy of the intermediate state is small and the closure approximation can be applied. It replaces the virtual energies of the intermediate states E_m by an average energy $\langle E_m \rangle$ and the sum of the intermediate states is taken as $\Sigma_m | 1^+_m \rangle \langle 1^+_m | = 1$. The advantage is that only the wavefunctions of the initial and final states are required and the complex calculations of the intermediate states can be avoided. Also, because $qR > 1$ (R being the radius of the nucleus) the expansion in multipoles does not converge and all multipoles contribute, not only 1^+. The generally accepted view is that the matrix elements are known within a factor of 2–3.

The importance of their precise knowledge for a neutrino mass determination, evident from equation (9), led to some new experimental effort to measure these elements. The idea is to study processes with known particles, where the same nuclear transitions as in double beta decay are involved. Ways pursued are charge exchange reactions with proton (^{3}He) beams and emitting neutrons (tritons) in the forward direction or muon-capture on nuclei of the daughter nucleus of a double beta isotope, since this would populate the states in the intermediate nucleus.

5. Experimental considerations

The search for $0\nu\beta\beta$-decay relies on finding a peak in the region below 4.3 MeV, depending on the isotope. Common to all experimental approaches is the aim for a very low-background environment due to 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 radioisotopes produced in materials while on the surface. To reduce contributions of atmospheric muons and their interaction products such experiments have to be performed deep underground.

All direct experiments focus 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 more information such as the measurement of energy and tracks of both electrons separately, but usually have a smaller source strength. Some experiments will be described now in a little more detail.

5.1. *Direct counting experiments*

The major progress in the last decades in pushing half-life limits and increasing the sensitivity towards smaller and smaller neutrino masses is due to the usage of 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 allows only the measurement of the sum energy of the two electrons. A big step forward due to an increase in source strength was accomplished by using isotopically 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 % in ^{76}Ge in the form of five high purity Ge-detectors (HPGe). A background as low as 0.17 counts/year/kg/keV at the peak position has been achieved. After 53.9 kg × year of data taking the peak region reveals no signal and the obtained half-life limit is [25] $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ years (90% CL) which can be converted using equation (9) and the matrix elements given in [26] 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, has reevaluated the data and found a small peak at the expected position [27,28] (figure 6). Taking the peak as real would point towards a half-life between 0.6–7.3 × 10^{25} years. Using the matrix elements calculated in [26] this would imply a range for the neutrino mass of 0.2–0.6 eV, which might be widened by using other matrix element calculations. However, the discussion concerning this possible evidence is still quite controversial, for details see [29–33].

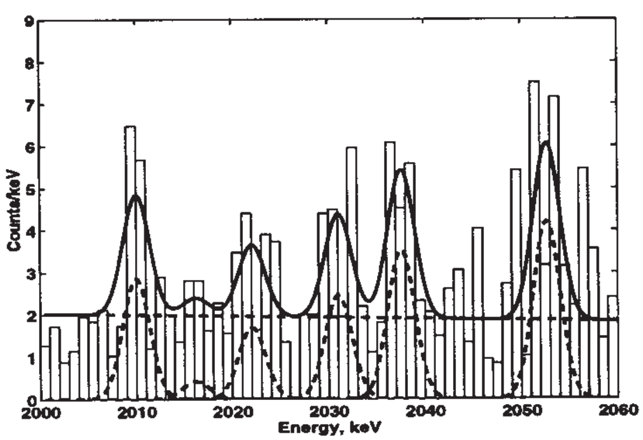

Figure 6. Energy spectrum of the Heidelberg-Moscow experiment around the $0\nu\beta\beta$-decay region at 2040 keV. The peak at 2039 keV is the claimed evidence (from [28]).

A $2\nu\beta\beta$-decay half-life was obtained by carefully subtracting all identified background sources. The obtained half-life is [25]

$$T^{2\nu}_{1/2} = 1.55 \pm 0.01^{+0.19}_{-0.15} \times 10^{21} \text{ years} \qquad (12)$$

The total amount of $2\nu\beta\beta$-decay events corresponds to more than 50 000 events.

Currently only two other large scale experiments are running. The first technique uses bolometers running at very low temperature (mK). The effect used here is the strong temperature dependence of the specific heat $C(T)$ of dielectric materials at these temperature scales. Therefore, the energy deposition ΔE of double beta decay would lead to a temperature rise of $\Delta T = \Delta E / C(T) M$, a significant rise in temperature if operating in the mK-range. Such detectors normally have a very good energy resolution of a few keV at 2 MeV. Currently, one such experiment (CUORICINO) is running at the Gran Sasso Underground Laboratory in Italy, using 62 TeO_2 crystals, corresponding to about 40 kg, at 8 mK to search for the ^{130}Te decay with a Q-value of 2529 keV [34]. The obtained half-life limit corresponds to [35] $T^{0\nu}_{1/2}(^{130}\text{Te}) > 5.3 \times 10^{23}$ year (90% CL).

The second experiment, NEMOIII in the Frejus Underground Laboratory, is of the form of a passive experiment, which are mostly built in the 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 the tracking of the two electrons is possible. Disadvantages are the energy resolution and in the case of thin foils the limited source strength. NEMOIII consists of a tracking (wire chambers) and a calorimetric (plastic scintillators) device put into a 30 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 6 kg). Their first measurement of the $2\nu\beta\beta$ decay of ^{100}Mo is shown in figure 7.

A compilation of obtained double beta results is shown in table 2. Observation of $2\nu\beta\beta$-decay has been quoted now for several isotopes. A compilation of measured half-lives is given in table 3. A complete listing of all experimental results obtained until the end of 2001 can be found in [36].

5.2. *Geochemical experiments*

The geochemical approach is to use old ores, which could have accumulated a significant amount of daughter nuclei due to double beta decay over geological timescales. This would lead to an isotopic anomaly which could be measured by mass spectrometry. Clearly the advantage of such experiments is the long exposure time of up to billion of years. Using the age T of the ore, and measuring the

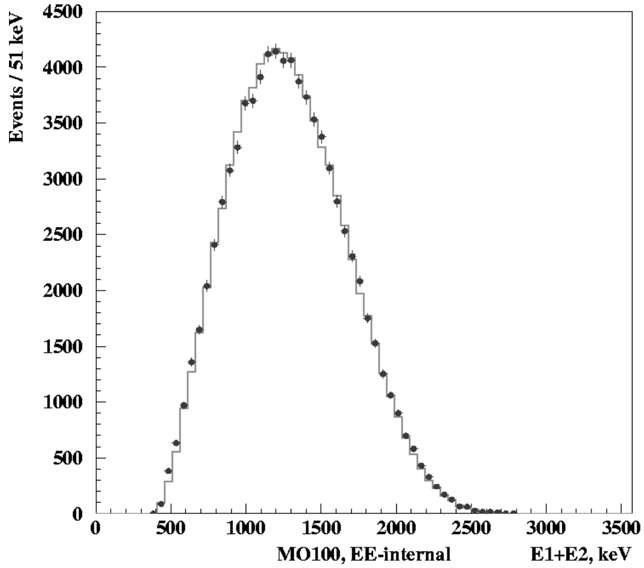

Figure 7. The sum energy spectrum of ^{100}Mo as obtained by the NEMOIII experiment agrees well with the expected spectral shape (line). The $2\nu\beta\beta$ spectrum is clearly visible (data points) and measured with low background (with kind permission of the NEMOIII experiment).

Table 2 Compilation of obtained limits for $0\nu\beta\beta$-decay. Notice, however, the claimed evidence for ^{76}Ge. All results are 90% CL, except ^{48}Ca (76 %) and ^{82}Se, ^{128}Te (68 %). * corresponds to a geochemical measurement, for details see text.

Isotope	Half-life limit (years)	ν mass limit (eV)
$^{48}_{20}$Ca $\rightarrow^{48}_{22}$ Ti	$>9.5\cdot10^{21}$ (76%)	<8.3
$^{76}_{32}$Ge $\rightarrow^{76}_{34}$ Se	$>1.9\cdot10^{25}$ (90%)	<0.35
$^{82}_{34}$Se $\rightarrow^{82}_{36}$ Kr	$>4\cdot10^{22}$ (68%)	<5.0
$^{100}_{42}$Mo $\rightarrow^{100}_{44}$ Ru	$>1\cdot10^{23}$ (90%)	<2.1
$^{116}_{42}$Cd $\rightarrow^{116}_{50}$ Sn	$>7\cdot10^{22}$ (90%)	<2.6
$^{128}_{52}$Te $\rightarrow^{128}_{54}$ Xe	$>7.7\cdot10^{24}$ (68%)	<1.1*
$^{130}_{52}$Te $\rightarrow^{130}_{54}$ Xe	$>7.5\cdot10^{23}$ (90%)	<0.85
$^{136}_{54}$Xe $\rightarrow^{136}_{56}$ Ba	$>4.4\cdot10^{23}$ (90%)	<2.3
$^{150}_{60}$Nd $\rightarrow^{150}_{62}$ Sm	$>2.1\cdot10^{21}$ (90%)	<4.1

Table 3. Compilation of obtained half-lives for $2\nu\beta\beta$-decay.

Isotope	Experiment	$T_{1/2}(10^{20}y)$
^{48}Ca	Calt.-KIAE	$0.43^{+0.24}_{-0.11}\pm0.14$
^{76}Ge	MPIK-KIAE	$15.5\pm0.1^{+1.9}_{-1.5}$
^{76}Ge	IGEX	11 ± 1.5
^{82}Se	NEMO 3	$1.03\pm0.03\pm0.07$
^{100}Mo	ELEGANT V	$0.115^{+0.03}_{-0.02}$
^{100}Mo	NEMO 3	$0.0768\pm0.0002\pm0.0054$
^{100}Mo	UCI	$0.0682^{+0.0038}_{-0.0053}\pm0.0068$
^{116}Cd	NEMO 2	$0.375\pm0.035\pm0.021$
^{116}Cd	ELEGANT V	$0.26^{+0.09}_{-0.05}$
^{116}Cd	ELEGANT V	$0.26^{+0.07}_{0.04}$
^{128}Te*	Wash. Uni-Tata	77000 ± 4000
^{238}U		20 ± 6

abundance of the mother $N(Z,A)$ and daughter $N(Z\pm2, A)$ isotope the decay rate can be determined from the exponential decay law ($t\ll T_{1/2}$)

$$\lambda \simeq \frac{N(Z\pm2,A)}{N(Z,A)}\times\frac{1}{T}. \tag{13}$$

As only the total amount of the daughter is observed, this kind of measurement does not allow differentiation between the production mechanisms, therefore the measured decay rate is $\lambda = \lambda_{2\nu} + \lambda_{0\nu}$. From practical considerations, only Se and Te-ores are usable. ^{82}Se, ^{128}Te and ^{130}Te decay to inert noble gases (^{82}Kr, ^{128,130}Xe). The detection of the small expected isotopical anomaly in Kr or Xe is made possible due to the large sensitivity of noble gas mass spectrometry [37]. After initial experiments of this type were already done in 1949, the first convincing evidence for double beta decay was observed in experiments using selenium and tellurium-ores [37–39]. Newer measurements can be found in [37,40,41].

5.3. *Radiochemical experiments*

This method takes advantage of the radioactive decay of the daughter nuclei, allowing a shorter 'measuring' time than geochemical experiments ('milking experiments'). No information on the decay mode can be obtained, only the total concentration of daughter nuclei is measured.

Two possible candidates are the decays ^{232}Th→^{232}U and ^{238}U→^{258}Pu with Q-values of 850 keV (^{232}Th) and 1.15 MeV (^{238}U) respectively. Both daughters are unstable against α-decay with half-lives of 70 years (^{232}Th) and 87.7 years (^{238}U). For the detection of the ^{238}U→^{238}Pu decay, the emission of a 5.5 MeV α-particle from the ^{238}Pu decay is used as a signal. The first experiment of this type was already done in 1950 using a six year old UO_3 sample. From the non-observation of the 5.51 MeV α-particles they deduced a lower limit of $T^{0\nu}_{1/2}(^{238}\mathrm{U})>6\times10^{18}$ years. Recently, a sample of 8.47 kg of uranium nitrate, which was purified in 1956 and analysed in 1989, was investigated, and a half-life of $T^{2\nu}_{1/2}(^{238}\mathrm{U})=(2.0\pm0.6)\times10^{21}$ years was obtained [42].

Both types, geo- and radiochemical methods, are measuring only the total decay rate by examining the concentration of the daughter nuclei. Hence, they are not able to distinguish between the different decay modes and their sensitivity is finally limited by $2\nu\beta\beta$-decay. This makes it almost impossible to establish real positive evidence for the neutrinoless mode by these methods.

6. Interpretation of the obtained results

As already stated the best limit for $0\nu\beta\beta$-decay is obtained with ^{76}Ge by the Heidelberg-Moscow experiment giving an upper bound of 0.35 eV for $\langle m_{\nu_e}\rangle$. The possible evidence of a peak is discussed later.

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, double charged Higgs bosons, R-parity violating SUSY couplings, leptoquarks and other Beyond Standard Model physics. Assuming 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

$$H = \frac{G_F cos\theta_C}{\sqrt{2}}(j_L J_L^\dagger + \kappa j_L J_R^\dagger + \eta j_R J_L^\dagger + \lambda j_R J_R^\dagger), \qquad (14)$$

with G_F being the Fermi constant, cos θ_c the Cabibbo angle and the left- and right-handed leptonic currents given as

$$j_L^\mu = \bar{e}\gamma^\mu(1-\gamma_5)\nu_{eL}, \quad j_R^\mu = \bar{e}\gamma^\mu(1+\gamma_5)\nu_{eR}, \qquad (15)$$

respectively. The coupling constants κ, η and λ vanish in the standard model. It can be shown that in gauge theories the neutrino mass and right handed current mechanisms are connected and a positive observation of $0\nu\beta\beta$-decay would prove a finite Majorana mass term [43,44]. The reason is that, regardless of the mechanism causing $0\nu\beta\beta$-decay, the two emitted electrons together with the two u, d quarks that are involved in the $n\to p$ transition can be coupled to the two ν_e in a way that a neutrino–antineutrino transition as in the Majorana mass term occurs. Expression (9) can be generalised if right-handed currents are included to

$$\begin{aligned}(T_{1/2}^{0\nu})^{-1} = C_{mm}\left(\frac{\langle m_{\nu_e}\rangle}{m_e}\right)^2 + C_{\eta\eta}\langle\eta\rangle^2 \\ + c_{\lambda\lambda}\langle\lambda\rangle^2 + C_{m\eta}\left(\frac{\langle m_{\nu_e}\rangle}{m_e}\right)\langle\eta\rangle \\ + C_{m\lambda}\left(\frac{\langle m_{\nu_e}\rangle}{m_e}\right)\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle,\end{aligned} \qquad (16)$$

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

$$\eta = \eta\sum_j U_{ej}V_{ej}, \quad \langle\lambda\rangle = \lambda\sum_j U_{ej}V_{ej}, \qquad (17)$$

with V_{ej} being the mixing matrix elements among the right-handed neutrino states. Equation (16) reduces to equation (9) in the case $\langle\eta\rangle$, $\langle\lambda\rangle = 0$. For example the element C_{mm} is given by

$$C_{mm} = G^{0\nu}|M^{0\nu}|^2. \qquad (18)$$

Allowing also right-handed currents to contribute, $\langle m_{\nu_e}\rangle$ is fixed by an ellipsoid, a two dimensional projection (suppressing $\langle\eta\rangle$) is shown in figure 8. The weakest mass limit allowed occur for $\langle\lambda\rangle$, $\langle\eta\rangle \neq 0$. In this case the half-life of ^{76}Ge corresponds to limits of $\langle m_{\nu_e}\rangle < 0.56\ eV$, $\langle\eta\rangle < 6.5 \times 10^{-9}$ and $\langle\lambda\rangle < 8.2 \times 10^{-7}$, respectively.

Of course, the whole discussion of limits changes, if the claimed observation of a neutrinoless double beta peak is real. Together with the oscillation results, this would fix the neutrino masses on the absolute scale. The claimed mass region of 0.2–0.6 eV (more appropriately the half-life range of $0.7-22.4 \times 10^{25}$ years should be claimed, because the given mass range is based on one specific set of nuclear matrix elements only) would also prove that the almost degenerate mass model is correct. Three neutrinos in that mass range would then determine the total contribution of neutrinos to the mass density in the Universe to be around 3%, still more than all the observed stars and dust, but less then the total amount of baryons as determined from big bang nucleosynthesis.

6.1. *Majoron accompanied decays*

A completely new class of decays emerges in connection with the emission of a Majoron χ [45]

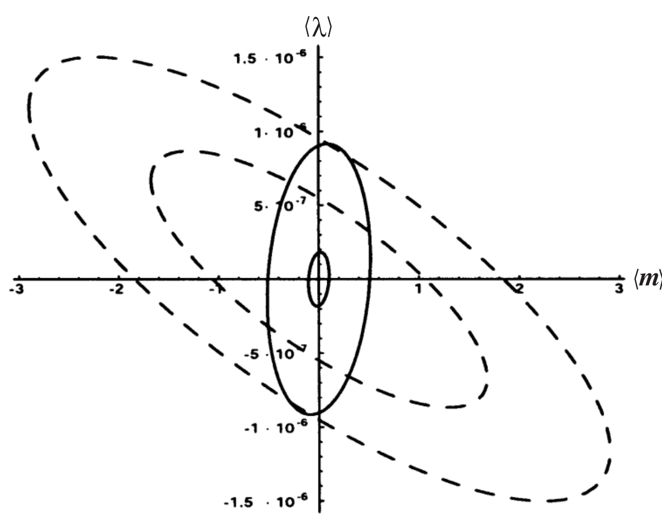

Figure 8. Two-dimensional projection in parameter space using the neutrino mass $\langle m\rangle$ and the right-handed coupling constant $\langle\lambda\rangle$. The allowed region corresponding to the possible evidence for $0\nu\beta\beta$-decay claimed in [28] is shown (solid lines), compared with a possible measurement of β^+/EC (dashed lines) with about the same half-life. As can be seen, a measurement of the β^+/EC mode provides more-or-less orthogonal constraints and will help to disentangle the underlying physics mechanism.

$$(Z, A) \rightarrow (Z+2, A) + 2e^- + \chi. \quad (19)$$

This hypothetical particle might exist, if lepton number is violated, as would be the case if neutrinoless double beta decay is observed. In case lepton number is a global symmetry spontaneously broken, the associated Goldstone boson is called majoron. A consequence for experiments is a different shape of the sum energy spectrum of the electrons. The predicted differential energy spectrum is

$$\frac{dN}{dK} \propto (Q-K)^n (1 + 2K + \frac{4K^2}{3} + \frac{K^3}{3} + \frac{K^4}{30}), \quad (20)$$

where K is the sum energy of both electrons and the spectral index n is 1,3 or 7 for various proposed theoretical Majoron models (see figure 4). The different shape allows a discrimination with respect to $2\nu\beta\beta$-decay, where $n = 5$. In the $n = 1$ model the effective neutrino-Majoron coupling $\langle g_{\nu\chi} \rangle$ can be deduced from

$$(T_{1/2}^{0\nu\chi})^{-1} = |M^{0\nu\chi}|^2 \, G^{0\nu\chi} |\langle g_{\nu\chi} \rangle|^2, \quad (21)$$

where $\langle g_{\nu\chi} \rangle$ is given by

$$\langle g_{\nu\chi} \rangle = \sum_{i,j} g_{\nu\chi} U_{ei} U_{ej}. \quad (22)$$

Present half-life limits for the decay mode ($n = 1$) are of the order $10^{21}-10^{22}$ years resulting in a deduced upper limit on the coupling constant of $\langle g_{\nu\chi} \rangle \lesssim 10^{-4}$. Recent compilations of available limits can be found in [1,46].

7. Future

Several upgrades are planned or proposed to improve the current situation. They are motivated by two facts. First of all, it is of course of major importance to confirm the claimed evidence with another isotope. CUORICINO and NEMOIII are in the best position because of being running experiments. If the peak is found not to be correct, the second aim is for a mass sensitivity below 50 meV, suggested by neutrino oscillation results and allowing us to discriminate the various neutrino mass scenarios (figure 1). The best way of improving sensitivity is by isotopical enrichment and by trying to make the experiment background free. However, an improvement of at least an order of magnitude in mass sensitivity implies more than two orders of magnitude improvement in half life. This implies large scale (several hundred kilograms of material) experiments and the $2\nu\beta\beta$-decay becomes now prominent as an irreducible background component. The reason is that the tail of $2\nu\beta\beta$-decay leaks into the peak region of $0\nu\beta\beta$-decay, because it occurs with typical 5–7 orders of magnitude higher rate. The crucial quantity for keeping this background under control is the energy resolution of the detector.

All the newly proposed projects can basically be separated into two groups: first, experiments which explore and improve already existing technologies (like GENIUS, MAJORANA, CUORE, SUPER-NEMO) and secondly really new experimental ideas (like COBRA, EXO, XMASS, MOON). For recent overviews about all planned or proposed experiments see [35,46]. A historic projection of the improvement in double beta decay is shown in figure 9.

8. Additional processes

The observation of $0\nu\beta\beta$-decay would imply a violation of total lepton number and hence physics beyond the standard model. However, the real observation might be two electrons only and the standard way to explain it is the exchange of a light Majorana neutrino between two neutrons. On the other hand any physics process beyond

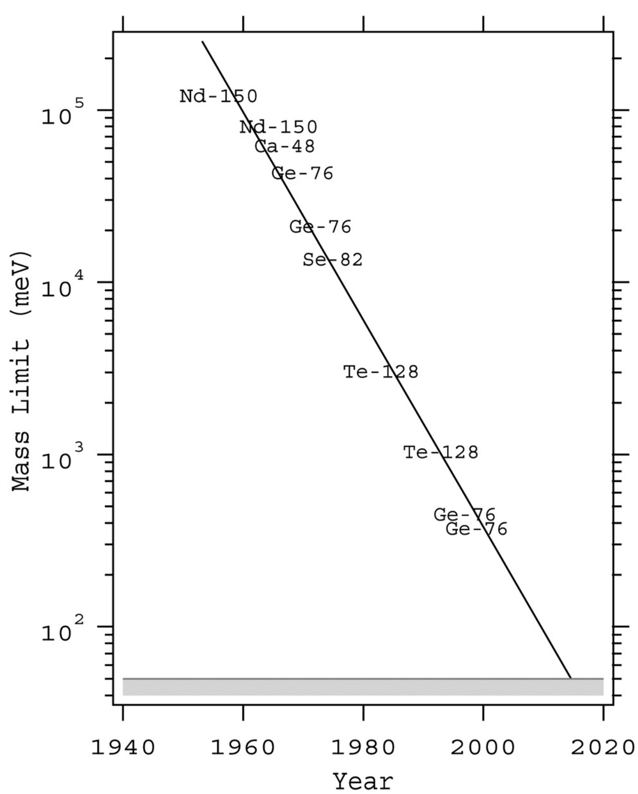

Figure 9. Development of the achieved neutrino mass limits as a function of time. The most important isotope under study at that time is shown. Following this extrapolation in about 10–15 years a sensitivity of 50 meV seems possible (with kind permission of S. Elliott, Los Alamos National Laboratory).

the standard model, which violates lepton number by two units might contribute to double beta decay. Candidates could be double charged Higgs bosons, right-handed weak currents, R-parity violating supersymmetry and so on. Hence, it is desirable whether there are further processes, helping to clarify which of all these underlying physics processes is actually the dominant one in $0\nu\beta\beta$-decay.

8.1. *Transition to excited states*

Isotope transition into the excited 0^+ and 2^+ states of the daughter nucleus can also be envisaged. The benefit could be twofold: first experimentally, the emission of the de-excitation gamma could form part of a good experimental signature to prove the occurrence of the transition. A second argument is of more theoretical interest, because transitions into excited 2^+ states are dominated by right-handed weak currents and an observation would prove their existence. The drawback is the reduction in the available phase space, being only $(Q - E_\gamma)$, where E_γ is the energy level of the excited state. Therefore, as long as no excited 2^+-state transition is observed, bounds on neutrino mass and right-handed coupling constants are much stronger, if obtained from the ground state transitions.

8.2. *$\beta^+\beta^+$-decay*

However, 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

$$\begin{aligned} (Z,A) &\rightarrow (Z-2,A) + 2e^+ + (2\nu_e), \\ e^- + (Z,A) &\rightarrow (Z-2,A) + e^+ + (2\nu_e), \\ 2e^- + (Z,A) &\rightarrow (Z-2,A) + (2\nu_e), \end{aligned} \tag{23}$$

where the last two cases involve electron capture (EC). Especially the β^+/EC mode shows an enhanced sensitivity to right handed weak currents [47]. 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 2 m_ec^2 , which leads to much smaller decay rates than in the comparable $0\nu\beta\beta$-decay. Hence, for $\beta^+\beta^+$ to occur, the Q-values must be at least 2048 keV. Only six isotopes are known to have such a high Q-value (table 4). The full Q-value is only available in the EC/EC mode. Its detection is experimentally more 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. This introduces an additional factor $\alpha_{em} = 1/137$ and thus reducing the rate to a level comparable to β^+/EC. Current half-life limits are of the order of 10^{20} years obtained with ^{106}Cd and ^{78}Kr for the modes involving positrons [36]. The COBRA experiment has the chance of simultaneously measuring five different isotopes for these decay channels [48]. As the decay is intrinsic to the CdZnTe semiconductor detectors one has a good chance of observing the 2ν EC/EC mode and for the positron emitting modes coincidences among the crystals can be used.

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

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

8.3. *Generalization to three flavours*

Nuclear double beta decay measures only one out of nine possible effective Majorana masses and the question arises as to what knowledge there is on the remaining eight. In general, there is a 3×3 matrix of effective Majorana masses, the elements being

$$\langle m_{\alpha\beta}\rangle = \left|\sum m_i U_{\alpha i} U_{\beta i}\right|, \tag{24}$$

with i = 1, 2, and 3 and α,β = e, μ, τ. Double beta decay measures the element $\langle m_{\nu_e}\rangle = \langle m_{ee}\rangle$. Which processes would give information on the other eight mass terms? It should be mentioned here, that currently all obtained possible bounds on those quantities are unphysical. The reason for this is the propagator term, containing both the W-boson and the Majorana neutrino masses. As long as the neutrino is much lighter than the W-boson of about 80.3 GeV mass the cross-section rises with energy. However, if the exchanged neutrino is heavier than the W-boson, the cross-section decreases with energy. Clearly, there must be a turnover point in the GeV range, as both masses are roughly the same. As calculations have shown [50,52,55] no experimental search is sensitive enough yet to probe the range of predicted cross-sections. Thus, in the following only the processes are mentioned but no mass limits are given.

A process closely related to double beta decay and, within the context discussed here, is the measurement of $\langle m_{e\mu}\rangle$, the muon-positron conversion on nuclei

$$\mu^- + (A, Z) \to e^+ + (A, Z-2). \qquad (25)$$

The current best 90% CL bound comes from SINDRUMII and is given by [49]

$$\frac{\Gamma(\mathrm{Ti} + \mu^- \to \mathrm{Ca}^{GS} + e^+)}{\Gamma(\mathrm{Ti} + \mu^- \to Sc + \nu_\mu)} < 1.7 \times 10^{-12}. \qquad (26)$$

A recent calculation [51] comes to a cross-section ten orders of magnitude smaller than earlier ones, which will worsen any bound by five orders of magnitude. Clearly there must be a better understanding in calculating this cross-section to solve the discrepancy of ten orders of magnitude before trying to extract any kind of neutrino mass limit out of this process.

Three different kinds of searches can be considered for the investigation of $\langle m_{\mu\mu}\rangle$. One process under study is muon lepton – number violating ($\Delta L_\mu = 2$) trimuon production in neutrino – nucleon scattering via charged current reactions (CC)

$$\nu_\mu N \to \mu^- \mu^+ \mu^+ X, \qquad (27)$$

where X denotes the hadronic final state. Detailed calculations can be found in [52]. A further possibility for probing $\langle m_{\mu\mu}\rangle$ is to explore rare meson decays like the neutrinoless double muon decay of kaons

$$K^+ \to \pi^- \mu^+ \mu^+. \qquad (28)$$

A new upper limit on the branching ratio of

$$\frac{\Gamma(K^+ \to \pi^- \mu^+ \mu^+)}{\Gamma(K^+ \to \mathrm{all})} < 3 \times 10^{-9} \quad (90\%\mathrm{CL}), \qquad (29)$$

has been measured [53]. Probably the closest analogue to performing a measurement on nuclear scales would be μ^- – capture by nuclei with a μ^+ in the final state as discussed in [54]. No such experiment has yet been performed, probably because of the requirement of using radioactive targets due to energy conservation arguments. Limits for mass terms involving the τ-sector were obtained by using data from the ep-collider HERA [55]. The process studied is

$$e^\pm p \to \overset{(-)}{\nu_e}\, l^\pm l'^\pm X, \qquad (30)$$

with $(ll') = (e\tau)$, $(\mu\tau)$, $(\mu\mu)$ and $(\tau\tau)$. Such a process has a spectacular signature with a large missing transverse momentum and two like – sign leptons, isolated from the hadronic remnants.

In summary, only the $0\nu\beta\beta$-decay discussed in large detail is sensitive enough to neutrino masses. The expected rates of all other processes discussed in this section are smaller than the experimental limits by several orders of magnitude. One main reason for this is, that nuclear double beta decay deals with kilograms of materials, implying a source of the order of 10^{25} atoms for searching for the decay, while all the other bounds are obtained with particle beams, where the available source is more of the order of 10^{10-15} particles. Nevertheless it is worthwhile considering these additional processes because as in the case of $0\nu\beta\beta$-decay they might provide stringent bounds on other quantities like those coming from R-parity violating SUSY and the sensitivity of the searches might improve significantly in the future.

9. Summary

While the observed $2\nu\beta\beta$-decay is among 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 $\Delta L = 2$ processes can severely restricted.

Neutrinoless double beta decay probes several important questions in physics. First of all it is the gold plated channel for probing the fundamental character of neutrinos, whether being its only antiparticle or not. Secondly it determines the absolute mass scale of neutrinos and might be able to discriminate among the different neutrino mass models currently discussed. Last, but not least, this might be the only opportunity for accessing two further possible CP-violating phases associated with the Majorana character of the neutrino. This might be important in the context of baryogenesis, the observed baryon asymmetry in the Universe. The idea behind leptogenesis is to produce a lepton asymmetry due to heavy Majorana neutrino decays in the very early universe, which at the electroweak phase transition will be partly transformed into a baryon asymmetry. Independently of these additional benefits, the proof that neutrinos are massive Majorana particles, is by itself sufficient to justify any effort to detect this rare process.

10. Acknowledgement

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References

[1] Zuber, K., 1998, *Phys. Rep.*, **305,** 295.
[2] Zuber, K., 2004, *Neutrino Physics* (Bristol: IOP Publishing).
[3] Ahmad, Q. R., *et al.*, 2002, *Phys. Rev. Lett.*, **89,** 011301.
[4] Ahmed, S. N., *et al.*, 2004, *Phys. Rev. Lett.*, **92,** 181301.
[5] Eguchi, K., *et al.*, 2003, *Phys. Rev. Lett.*, **90,** 021802.
[6] Fukuda, Y., *et al.*, 1998, *Phys. Rev. Lett.*, **81,** 1582.
[7] Armbruster, B., *et al.*, 2002, *Phys. Rev.* D, **65,** 112001.
[8] Athanassopoulos, C., *et al.*, 1998, *Phys. Rev.* C, **58,** 2489.

[9] Astier, P., *et al*., 2003, *Phys. Lett*. B, **570,** 19.
[10] Weinheimer, C., 2003, *Nucl. Phys*. B (Proc. Suppl.), **118,** 279.
[11] Bennett, C. L., *et al*., 2003, *Astroph. J. Suppl*., **148,** 1.
[12] Spergel, D. N., *et al*., 2003, *Astroph. J. Suppl*., **148,** 175.
[13] Goeppert-Mayer, M., 1935, *Phys. Rev*., **48,** 512.
[14] Majorana, E., 1937, *Nuovo Cimento*, **14,** 171.
[15] Racah, G., 1937, *Nuovo Cimento*, **14,** 322.
[16] Furry, W., 1939, *Phys. Rev*., **56,** 1184.
[17] Boehm, F., and Vogel, P., 1992, *Physics of Massive Neutrinos* (Cambridge: Cambridge University Press).
[18] Haxton, W. C., and Stephenson, G. J., 1984, *Prog. Nucl. Part. Phys*., **12,** 409.
[19] Doi, M., Kotani, T., and Takasugi, E., 1985, *Prog. Theo. Phys. Suppl*., **83,** 1.
[20] Muto, K., and Klapdor, H. V., 1988, in *Neutrinos*, edited by H. V. Klapdor (Springer, Heidelberg), pp. 183–238.
[21] Grotz, K., and Klapdor, H. V., 1990, *The Weak Interaction in Nuclear, Particle and Astrophysics* (Bristol: Hilger).
[22] Faessler, A., and Simkovic, F., 1998, *Journal of Physics G*, **24,** 2139.
[23] Suhonen, J., and Civitarese, O., 1998, *Phys. Rep*., **300,** 123.
[24] Ericson, M., Ericson, T., and Vogel, P., 1994, *Phys. Lett*. B, **328,** 259.
[25] Klapdor-Kleingrothaus, H. V., *et al*., 2001, *Europ. Phys. J*. A, **12,** 147.
[26] Staudt, A., Muto, K., and Klapdor-Kleingrothaus, H. V., 1990, *Europhys. Lett*., **13,** 31.
[27] Klapdor-Kleingrothaus, H. V., *et al*., 2002, *Mod. Phys. Lett. A*, **16,** 2409.
[28] Klapdor-Kleingrothaus, H. V., *et al*., 2004, *Phys. Lett*. B, **586,** 198.
[29] Aalseth, C. E., *et al*., 2002, *Mod. Phys. Lett. A*, **16,** 2409.
[30] Feruglio, F., Strumia, A., and Vissani, F., 2002, *Nucl. Phys*. B, **637,** 345.
[31] Klapdor-Kleingrothaus, H. V., Preprint hep-ph/0205228.
[32] Harney, H. L., Preprint hep-ph/0205293.
[33] Zdesenko, Y. G., Danevich, F. A., and Tretyak, V. I., 2002, *Phys. Lett*. B, **546,** 206.
[34] Arnaboldi, C., *et al*., 2004, *Phys. Lett*. B, **584,** 260.
[35] Cremonesi, O., 2003, *Nucl. Phys*. B (Proc. Suppl.), **118,** 287.
[36] Tretyak, V. I., and Zdesenko, Y. G., 2002, *At. Dat. and Nucl. Dat. Tab*., **80,** 83.
[37] Kirsten, T., 1986, *Proc. Int. Symp. on Nuclear Beta Decays and Neutrinos*, edited by T. Kotani, H. Ejiri, and E. Takasugi (Osaka: World Scientific), p. 81.
[38] Kirsten, T., Gentner, W., and Schaeffer, O. A., 1967, *Z. Phys*., **202,** 273.
[39] Kirsten, T., Gentner, W., and Schaeffer, O. A., 1968, *Phys. Rev. Lett*., **20,** 1300.
[40] Lin, J. W., *et al*., 1988, *Nucl. Phys*. A, **481,** 477.
[41] Bernatowicz, T., *et al*., 1993, *Phys. Rev*. C, **47,** 806.
[42] Turkevich, A. I., Economou, T. E., and Cowen, G. A., 1992, *Phys. Rev. Lett*., **67,** 3211.
[43] Schechter, J., and Valle, J. W. F., 1982, *Phys. Rev*. D, **25,** 2591.
[44] Takasugi, E., 1984, *Phys. Lett*. B, **149,** 372.
[45] Doi, M., Kotani, T., and Takasugi, E., 1988, *Phys. Rev*. D, **37,** 2575.
[46] Elliott, S., Vogel, P., 2002, *Ann. Rev. Nucl. Part. Phys*., **52,** 115.
[47] Hirschet, M., *et al*., 1994, *Z. Phys*. A, **347,** 151.
[48] Zuber, K., 2001, *Phys. Lett*. B, **519,** 1.
[49] Kaulard, J., *et al*., 1998, *Phys. Lett*. B, **422,** 334.
[50] Zuber, K., 2002, *Prog. Nucl. Part. Phys*., **48,** 223.
[51] Simkovic, F., *et al*., Preprint hep-ph/0103029.
[52] Flanz, M., Rodejohann, W., and Zuber, K., 2000, *Europ. Phys. J*. C, **16,** 453.
[53] Appel, R., *et al*., 2000, *Phys. Rev. Lett*., **85,** 2877.
[54] Missimer, J. H., Mohapatra, R. N., and Mukhopadhyay, N. C., 1994, *Phys. Rev*. D, **50,** 2067.
[55] Flanz, M., Rodejohann, W., and Zuber, K., 2000, *Phys. Lett*. B, **473,** 324.

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