Status and perspectives of double beta decay searches

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2015 J. Phys.: Conf. Ser. 578 012007
(http://iopscience.iop.org/1742-6596/578/1/012007)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 131.169.4.70
This content was downloaded on 19/01/2016 at 22:59

Please note that terms and conditions apply.
Status and perspectives of double beta decay searches

Kai Zuber
Institut für Kern- und Teilchenphysik, TU Dresden, 01069 Dresden, Germany
E-mail: zuber@physik.tu-dresden.de

Abstract. Double beta decay is an extremely rare process and requires half-life measurements around $10^{20}$ years for the neutrino accompanied mode, while for the neutrino-less mode much longer half-lives have to be explored. The various experimental approaches, currently considered for the search of this process, results will be presented.

1. Introduction and physics
Neutrinos play a crucial role in modern particle, nuclear and astrophysics including cosmology. It has been the major achievement of the last 15 years to show that neutrinos have a non-vanishing rest mass. The evidence arises from a deficit of upward going atmospheric muon neutrinos confirmed by long baseline accelerator experiments and the solution of the solar neutrino problem being confirmed by nuclear reactor measurements. All observations can be explained by neutrino oscillations, which are depending on mass differences $\Delta m^2_{ij} = m^2_j - m^2_i$ with $i,j = 1,2,3$. The determination of absolute neutrino masses is now a major issue, because neutrino oscillation experiments do not allow this. The classical way to search for a rest mass of the neutrino is the study of the endpoint region of electron spectra in beta decay (see [1] for a recent review). The KATRIN experiment is well on its way to improve the current bound of about 2.2 eV for $\bar{\nu}_e$ by an order of magnitude. Further bounds on the total sum of neutrino masses can be obtained from cosmological studies, dominated by recent Planck measurements combined with large scale structure information based on BAO suggesting that the mass is less than about 0.25 eV [2]. Another laboratory process to search for neutrino masses is the rare nuclear decay of neutrino-less double beta decay

\[(Z, A) \rightarrow (Z + 2, A) + 2e^- \quad (0\nu\beta\beta-\text{decay}) \quad (1)\]

accompanied by the Standard Model process of

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

Single beta decay must be forbidden or at least strongly suppressed to observe this decay and only 35 potential double beta emitter exist in nature. As can be seen from Equation 1 the given decay mode is violating total lepton number by two units and thus is not allowed in the Standard Model. Being a decay the observable is a half-life which can be linked to the quantity of interest $\epsilon$ via

\[ (T_1^{0\nu})^{-1} = G_{PS} \left| M_{Nuc} \right|^2 \epsilon^2 \quad (3) \]
with $G_{PS}$ being the phase space, $|M_{Nue}|$ the involved nuclear matrix element for the physics process considered to describe this decay and $\epsilon$ the quantity of interest. Various beyond the Standard Model processes can be considered like light and heavy Majorana neutrino exchange, right-handed weak currents, R-parity violating SUSY ($\lambda'_{111}$) and double charged Higgs bosons. Independent of the dominant decay mechanism, if $0\nu\beta\beta$-decay is ever observed experimentally it will imply that neutrinos are Majorana particles [3]. Furthermore, given all the possible processes it will become an important question what the individual contributions of the considered processes will be. The LHC will help to restrict this by performing searches for new particles in the TeV range. An example how this complementary information from LHC and $0\nu\beta\beta$-decay can be used within the context of left-right symmetric theories is given in [4]. For a recent extensive review on the particle physics in double decay see [5].

The standard interpretation considered here is the one using light Majorana neutrino exchange. In this case $\epsilon$ is the effective Majorana neutrino mass $\langle m_{ee} \rangle$ given by

$$\epsilon \equiv \langle m_{ee} \rangle = |\sum_i U_{ei}^2 m_i|$$

with $U_{ei}^2$ as the PMNS-mixing matrix elements containing the electron neutrino.

2. Double beta decay and neutrino oscillation results

For the following discussion a restriction to the light Majorana neutrino case is done. It is evident from Eq. 4 that the expectation for $\langle m_{ee} \rangle$ in double beta decay depends on the neutrino oscillation parameters. It should be noted that the mixing matrix of relevance is given by

$$U = U_{PMNS}(\theta_{12}, \theta_{13}, \theta_{23}, e^{i\delta}) \times diag(1, e^{i\alpha}, e^{i\beta})$$

with the standard leptonic mixing matrix $U_{PMNS}$ and two additional CP-phases $\alpha$ and $\beta$, called Majorana phases, which appear if a neutrino is its own antiparticle. These phases do not show up in oscillation experiments. Hence, $\langle m_{ee} \rangle$ can be written as a sum of three terms

$$\langle m_{ee} \rangle = |m_1^2| + |m_2^2| e^{2i\alpha} + |m_3^2| e^{2i\beta}$$

with the individual contributions given as

$$m_1^2 = |U_{e1}|^2 m_1 = m_1 \cos^2 \theta_{12} \cos^2 \theta_{13}$$
$$m_2^2 = |U_{e2}|^2 m_2 = m_2 \sin^2 \theta_{12} \cos^2 \theta_{13}$$
$$m_3^2 = |U_{e3}|^2 m_3 = m_3 \sin^2 \theta_{13}$$

Latest global fits to available oscillation parameters are given in [6, 7]. An important new ingredient are 3-flavour fits to solar neutrinos [8], observations from T2K [9] and MINOS [10] as well as first direct measurements of $\theta_{13}$ from the reactor experiments Double Chooz, Daya Bay and RENO [11, 12, 13, 14]. As the oscillations do not fix the absolute scale there are two options for arranging the mass eigenstates, either $m_3 > m_2 > m_1$ (normal hierarchy, NH) or $m_1 > m_2 > m_3$ (inverse hierarchy, IH). If the neutrino masses turn out to be close to the current limit from beta decay there is a quasidegeneracy ($m_1 \approx m_2 \approx m_3 \approx m_0$). In case of hierarchies the two larger masses can be expressed as

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2} \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2} \quad \text{(normal)}$$
$$m_2 = \sqrt{m_3^2 + \Delta m_{23}^2} \quad m_1 = \sqrt{m_3^2 + \Delta m_{13}^2} \quad \text{(inverted)}$$

with the solar splitting $\Delta m_{21}^2 = 7.59_{-0.18}^{+0.20} \times 10^{-5} eV^2$ and the atmospheric splitting $\Delta m_{31}^2 = 2.49 \pm 0.09 \times 10^{-3} eV^2$ (normal), $\Delta m_{13}^2 = -2.343_{-0.09}^{+0.10} \times 10^{-3} eV^2$ (inverted) [6]. The behaviour
Figure 1. A presentation (as introduced by [15]) of the effective Majorana neutrino mass $\langle m_{ee} \rangle$ as a function of the lightest mass eigenstate. Shown are the inverted (green) and normal (red) hierarchy bands using the current values of the mixing angles and their 1$\sigma$ and 3$\sigma$ range. As can be seen within the normal hierarchy there can be perfect cancellation of terms in case that the lightest neutrino mass is in the range $10^{-3} - 10^{-2}$ eV (1$\sigma$) or even $10^{-4} - 10^{-2}$ eV (3$\sigma$).

For $\langle m_{ee} \rangle$ values larger than about 100 meV neutrinos are almost degenerate, the inverted hierarchy covers a range between about 10-50 meV and below 10 meV is the region of the normal hierarchy. As can be seen, in the NH there is a chance for cancellation among the terms (Fig. 1). There is no such effect in the IH because of the non-maximal solar mixing angle $\theta_{12}$. Half-lives for the IH are in the region beyond $10^{26}$ years while half-lives in the NH are well beyond $10^{28}$ years.

3. General experimental considerations
Historically three different kinds of methods have been used, radiochemical (basically searching for the double beta decay of $^{238}$U), geochemical (exploring billion years old ores) and direct searches. Nowadays the first two methods are of less importance as they cannot distinguish between the different decay modes and are considered to be dominated by $2\nu\beta\beta$-decay, Equation (2).

Evidently measurements of half-lives around $10^{20}$ years and well beyond are by no means trivial. As signal for the process given in Equation (1) serves a peak in the sum energy spectrum of the two electrons equivalent to the Q-value of the nuclear transition. From Equation (1) it is also apparent that the maximal information obtainable from measurements will be the single electron energies, the opening angle between them and the daughter ion. This might be accompanied by
characteristic gamma rays in case of excited state transitions. The corresponding half-life in case of no background is given by the radioactive decay law (assuming a measuring time $t \ll T_{1/2}^{0\nu}$)

$$T_{1/2}^{0\nu} = \ln 2ma/N_A/N_{\beta\beta}$$

with $m$ the used mass, $a$ the isotopic abundance of the double beta emitter, $t$ the measuring time, $N_A$ the Avogadro constant and $N_{\beta\beta}$ the number of double beta events, which has to be taken from the experiment. If no peak is observed and a constant background (in general terms these are all potential energy depositions in the region of interest, i.e. around the Q-value, not being neutrino-less double beta decay) is assumed scaling linearly with time, a half-live estimate can be derived as

$$(T_{1/2}^{0\nu})^{-1} \propto a \times \epsilon \sqrt{M \times t/B \times \Delta E}$$

where $\epsilon$ is the efficiency for detection of the total energy of both electrons, $\Delta E$ is the energy resolution at the peak position and $B$ the background index normally given in counts/keV/kg/year. Hence, the most crucial parameters are a high detection efficiency and high abundance of the isotope of interest. This is the reason why almost all next generation experiments are using enriched materials and the "source = detector" approach, i.e. the emitter is part of the detector itself. Furthermore, the energy resolution\(^1\) should be as good as possible to concentrate the few expected events in a small region and ideally the experiment should be background free. An irreducible background is the Standard Model process $2\nu\beta\beta$-decay. Here again energy resolution matters, because of the continuous spectrum of the $2\nu\beta\beta$-decay mode, its high energy part is leaking into the peak region (see Figure (2)). Nevertheless, this can be

\[\text{Figure 2. Schematic plot of the sum energy spectrum of the two electrons in double beta decay, shown here for } ^{76}\text{Ge. } 0\nu\beta\beta\text{-decay results in a peak at the Q-value of the transition. Various modes can be characterised by the phase space dependence (Q-E)\(^n\). The mode } n=5 \text{ is the } 2\nu\beta\beta\text{-decay while the modes } n=1,3,7 \text{ involve the emission of a majoron, a Goldstone boson linked to the spontaneous breaking of lepton number. The different modes belong to different behaviours of the majoron with respect to weak isospin. The individual contributions are not to scale.} \]

\(^1\) Care must be taken when comparing experiments, as for traditional reasons different detector technologies use either the Gaussian $\sigma$ or the Full Width at Half Maximum $\Delta E$ to quote energy resolution. The relation among the quantities is $\Delta E = 2.35\sigma$. 


a worry as the half-life is typically several orders of magnitude shorter than the expected one for $0\nu\beta\beta$-decay. As the decay rate for $0\nu\beta\beta$-decay scales with $Q^5$ only isotopes with $Q$-values above 2 MeV are considered for experimental searches. They are listed together with their natural abundance and $Q$-value in Table (1).

| Isotope | nat. abund. (%) | Q-value (keV) | Experiment |
|---------|-----------------|---------------|------------|
| $^{48}$Ca | 0.187 | 4267.96 ± 0.32 | CANDLES |
| $^{76}$Ge | 7.8 | 2039.006 ± 0.050 | GERDA, MAJORANA |
| $^{82}$Se | 9.2 | 2995.5 ± 1.9 | SuperNEMO, LUCIFER |
| $^{96}$Zr | 2.8 | 3347.7 ± 2.2 | - |
| $^{100}$Mo | 9.6 | 3034.40 ± 0.17 | AMoRE |
| $^{110}$Pd | 11.8 | 2017.85 ± 0.64 | - |
| $^{116}$Cd | 7.5 | 2813.50 ± 0.13 | COBRA, CdWO$_4$ |
| $^{124}$Sn | 5.64 | 2292.64 ± 0.39 | (Tin.Tin) |
| $^{130}$Te | 34.5 | 2527.518 ± 0.013 | CUORE, SNO+ |
| $^{136}$Xe | 8.9 | 2457.83 ± 0.37 | EXO, KamiLAND-Zen, NEXT |
| $^{150}$Nd | 5.6 | 3371.38 ± 0.20 | MCT |

Table 1. Table showing the eleven candidate isotopes with a Q-value larger than 2 MeV. Given are the natural abundances and Q-values as determined from precise Penning trap measurements or from the Atomic Mass Evaluation 2012 [16]. The last column shows the experiments addressing the measurement of the corresponding isotope. For some experiments only the ”default” isotope is mentioned as they consider exploring several ones. Additionally, several other research and development projects are ongoing.

As mentioned, most experiments follow the approach that the source is equal to the detector, i.e., building a detector which contains the isotope of interest. Technologies used for that are semiconductors, cryogenic bolometers, scintillators and liquid noble gas detectors. The alternative is to use tracking devices in form of TPCs containing thin foils of double beta emitters. Here single electron spectra and opening angles can be measured as well.

4. Experimental status

Figure 3. Measured spectrum of the GERDA experiment in phase I. The search was performed as a blind analysis. No apparent peak is visible and the result strongly disfavors a claim made 10 years ago (from [19]).
The last years were dominated to set-up experiments being able to probe the claimed observation of $0\nu\beta\beta$-decay in $^{76}\text{Ge}$ [17]. The start has happened with new double beta experiments, namely GERDA (using $^{76}\text{Ge}$), EXO and KamLAND-Zen (using $^{136}\text{Xe}$) and CANDLES (using $^{48}\text{Ca}$). GERDA [18] is a next generation experiment based on Ge-semiconductors consisting of Ge-crystals enriched in $^{76}\text{Ge}$. The experiment is located in the Gran Sasso Underground Laboratory (Italy). The idea is to run the bare crystals within LAr which serves as shielding and cooling. In a first phase a total of eight isotopically enriched detectors (from the former Heidelberg-Moscow and IGEX experiments) with a total mass of 17.7 kg and three natural Ge-detectors have been deployed and official data taking started on 1. Nov. 2011. The spectrum in the region of interest at the end of phase 1 is shown in Figure (3). Apparently the data do not support the claim [19]. Currently the experiment is preparing for phase 2, which is aiming to reduce background by another order of magnitude and adding more detectors.

Due to the relative cheap enrichment of noble gases, two large scale experiments based on enriched $^{136}\text{Xe}$ have started. First is EXO-200, using about 175 kg LXe in form of a TPC located at WIPP (USA). Also EXO-200 could not find a peak and provide a lower limit of $1.1\times10^{25}$ yrs (90 \% CL) [20]. A second Xe approach is KamLAND-Zen using the well understood infrastructure of the KamLAND experiment. To perform double beta decay with Xe-loaded liquid scintillator a special mini-balloon was constructed and deployed within KamLAND. In this way about 330 kg of enriched Xe could be filled in the detector and data taking has started in September 2011. A lower half-life limit for the neutrinoless decay of $1.9\times10^{25}$ yrs (90 \% CL) is given [21]. Last but not least there is CANDLES using 305 kg of CaF$_2$ scintillators, focusing on $^{48}\text{Ca}$, the isotope with the highest $Q$-value of all double beta emitters. The experiment is installed in the Kamioka mine (Japan) and data taking has started recently.

As the evidence is not confirmed, the next goal will be to reach the region of the inverted hierarchy, i.e $(m_{ee})$ below $\approx 50$ meV. The requirement on the necessary half-life to touch this region is given in [22]. As the requirements on mass and background for this purpose are already very demanding, fully excluding the IH is more than challenging. If there is no signal found in the IH the ultimate step is the exploration of the normal hierarchy. However, for this ton scale experiments with extraordinary low background have to be considered and completely new background components have to taken into account, for example neutrino-electron scattering due to solar $^8\text{B}$ neutrinos [23]. For that half-lives well beyond $10^{28}$ yrs have to be measured.

5. Alternative processes including positrons and electron capture

An equivalent process to the one discussed is $\beta^+\beta^-$-decay also in combination with electron capture (EC). There are three different variants possible depending on the $Q$-value:

\begin{align}
(Z, A) & \rightarrow (Z - 2, A) + 2e^+ (+2\nu_e) \quad (\beta^+\beta^+) \quad (11) \\
\epsilon_{\beta^-} + (Z, A) & \rightarrow (Z - 2, A) + e^+ (+2\nu_e) \quad (\beta^+ / EC) \quad (12) \\
2\epsilon_{\beta^-} + (Z, A) & \rightarrow (Z - 2, A) (+2\nu_e) \quad (EC / EC) \quad (13)
\end{align}

$\beta^+\beta^+$ is always accompanied by EC/EC or $\beta^+ / EC$-decay. The positron production reduces the effective $Q$-value by $2m_{e}c^2$ per positron. Therefore, the rate for $\beta^+\beta^+$ is small and energetically only possible for six nuclides, however it would have a striking signature with four 511 keV gamma rays. It was shown that the $\beta^+ / EC$-mode has an enhanced sensitivity to right-handed weak currents [24] and might be valuable to explore if $0\nu\beta\beta$-decay is discovered. The full $Q$-value is available in the EC/EC mode which is the hardest to detect experimentally. However, it was proposed [25, 26] that if an excited state of the daughter nucleus is degenerate with the original ground state a resonance enhancement in the decay rate could occur and the de-excitation gammas would serve as a nice signal. Due to the sharpness of the resonance a
more detailed study of candidates had to wait for Penning traps entering the field and exploring reasonable candidates. The most reliable one seems to be $^{152}$Gd (see Figure 4) where such a scenario is realised [27]. Despite this nice effect, to achieve the same sensitivity of $\langle m_{ee} \rangle$ as in $0\nu\beta\beta$-decay seems to require a measurement of the half-life an order of magnitude longer making this method slightly less attractive. Decays have been searched for in a number of isotopes with half-life limits ranging from $10^{15} - 10^{21}$ years, but no signal could be found in direct searches. However there is a weak evidence from geochemical experiments for an effect in the $^{130}$Ba system [28, 29].

![Figure 4. Compilation of enhancement factors in resonant neutrino-less double electron capture based on mass measurements with Penning traps (from [27]).](image_url)

References
[1] Otten E and Weinheimer C 2008 Rep. Prog. Phys. 71 086201
[2] Ade P A R et al 2013 Preprint arXiv:1303.5076, arXiv:1311.1657
[3] Schechter J and Valle J W F 1981 Phys. Rev. D 23 1666
[4] Tello V et al 2011 Phys. Rev. Lett. 106 151801
[5] Rodejohann W 2011 Int. Journal of Modern Physics 20 1833
[6] Schuetz T, Tortola M and Valle J W F 2011 New J. Phys. 13 063004
[7] Fogli G L et al 2011 Phys. Rev. D 84 053007
[8] Aharmim B et al 2013 Phys. Rev. C 88 025501
[9] Abe K et al 2011 Phys. Rev. Lett. 107 041801
[10] Adamson P et al Phys. Rev. Lett. 110 251801
[11] Abe Y et al 2012 Phys. Rev. Lett 108 131801
[12] An F P et al 2012 Phys. Rev. Lett. 108 171803
[13] Ahn J K et al 2012 Phys. Rev. Lett. 108 191802
[14] Abe Y et al 2012 Preprint arXiv:1207.6632
[15] Vissani F 1999 JHEP 9906 022
[16] Wang M et al 2012 Chin. Phys. C 36 1603
[17] Klapdor-Kleingrothaus H V et al 2004 Phys. Lett. B 578 54
[18] Ackermann K-H et al 2013 Eur. Phys. J. C 73 2330
[19] Agostini M et al 2013 Phys. Rev. Lett. 111 122501
[20] Albert J B et al 2014 Preprint arXiv:1402.6956
[21] Gando A et al 2012 Phys. Rev. C 85 045504
[22] Dueck A, Rodejohann W and Zuber K 2011 Phys. Rev. D 83 113010
[23] deBarros N F and Zuber K 2011 J. Phys. G: Nucl. Phys. 38 105201
[24] Hirsch M et al 1994 Z. Phys. A 347 151
[25] Bernabeu J, DeRujula A and Jarlskog C 1983 Nucl. Phys. B 223 15
[26] Sujkowski Z and Wycech S 2004 *Phys. Rev. C* **70** 052501
[27] Eliseev S *et al* 2011 *Phys. Rev. Lett.* **106** 052504
[28] Barabash A and Saakyan R 1996 *Phys. Atom. Nucl.* **59** 179
[29] Meshik A P *et al* 2001 *Phys. Rev. C* **64** 035205