Long term prospects for double beta decay

Kai Zuber

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany

Abstract

In rather general terms the long term perspective of double beta decay is discussed. All important experimental parameters are investigated as well as the status of nuclear matrix element issues. The link with other neutrino physics results and options to disentangle the underlying physics process are presented.

1 Introduction

The lepton number violating process of neutrinoless double β-decay

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

plays a crucial role in neutrino physics. It can only occur if two conditions are fulfilled: A neutrino has to be its own antiparticle (called Majorana neutrino) AND it has to have a non-vanishing rest mass. For the moment this statement ignores any other lepton-number violating contribution from Beyond Standard Model physics. However, if $0\nu\beta\beta$-decay will ever be discovered the question will arise how to discriminate the various ideas experimentally. Nevertheless, Schechter and Valle have shown that the fact of observing neutrinoless double β-decay is equivalent of stating that neutrinos are Majorana particles independent of the dominant mechanism driving the decay [1]. The near term future of experimental activities over the next five years is covered in [2] and thus this article assumes most of the time that the claimed evidence [3] will not be confirmed. For the following discussion towards an "ultimate" double beta experiment a very general approach is taken to work out the important items.

One of the major equations governing this field is obviously the radioactive decay law. It can be written in the case that the half-life $T_{1/2}$ is much longer than the measuring time t as

$$N_{\beta\beta} = ln2 \times a \times M \times t \times N_A/T_{1/2} \tag{2}$$

with M as the used mass, a the isotopical abundance of the nuclide under interest and $N_{\beta\beta}$ as the number of double beta decays. How is this linked to experiment? The experimental signature of $0\nu\beta\beta$-decay is that the sum energy of the two emitted electrons equals the total nuclear transition energy, called the Q-value. Thus, in an experiment aiming to see two electrons with a fixed energy there are two options, either there are no other physics processes (including the allowed neutrino accompanied double beta decay $2\nu\beta\beta$-decay) doing exactly the same (background free) or you might have some events resulting in the region of interest (background). These result in different dependences of the expected half-life sensitivity as

$$(T_{1/2})^{-1} \propto a \times M \times \epsilon \times t \quad \text{(background free)} \tag{3}$$

$$(T_{1/2})^{-1} \propto a \times \epsilon \times \sqrt{\frac{Mt}{B\Delta E}} \quad \text{(background limited)} \tag{4}$$

with ϵ as the efficiency for detection, B the background index (typically quoted in counts/keV/kg/yr) and ΔE as the energy resolution at the peak position. Depending on the (non-)observation of a peak either a half-life or a lower limit on the half-life can be measured and linked to the neutrino mass via

$$(T_{1/2})^{-1} = PS^{0\nu} \times \mid M^{0\nu} \mid^2 \times (\frac{\langle m_{\nu_e} \rangle}{m_e})^2 \tag{5}$$
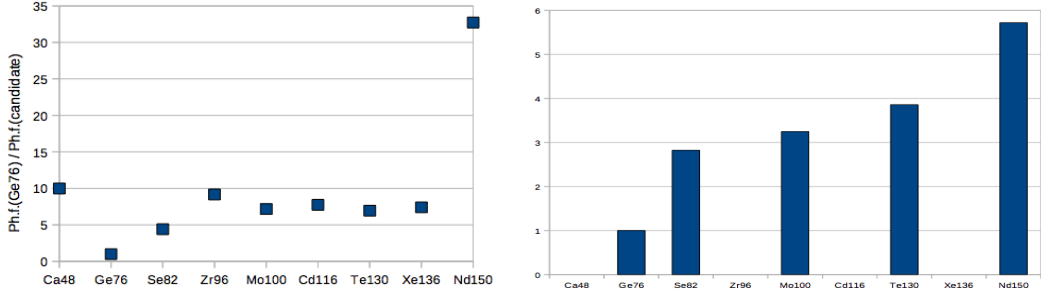
Fig. 1: Left: Phase space factors including Coulomb corrections for some of the most interesting isotopes, normalise to ^{76}Ge=1. Values taken from [4]. Right: Product of phase space and IBM matrix elements [8] as conversion factor of half-lives into neutrino masses. Again the plot is normalised to ^{76}Ge=1.

with $PS^{0\nu}$ as the phase space factor containing Coulomb corrections, $M^{0\nu}$ the nuclear transition matrix element and the effective Majorana neutrino mass $\langle m_{\nu_e} \rangle$ defined as

$$\langle m_{\nu_e} \rangle = \mid \sum U_{ei}^2 m_i \mid \tag{6}$$

with U_{ei} as the PMNS mixing matrix elements and thus constrained by oscillation results. It should be noted that due to the condition of requiring neutrinos to be Majorana particles two more CP-violating phases occur in the mixing matrix, in addition to the one which can be searched for in oscillation experiments.

Thus, the "ultimate" experiment is easy to define: Infinite measuring time, infinite number of source atoms, no background, a δ-function for energy resolution, 100 % efficiency and the largest possible phase space and nuclear matrix element. The question is how close this can be achieved. As the measuring time is something which cannot really be effected and most experiments using the "source=detector" approach have 100 % efficiency these two factors won't be discussed in the following.

2   Theoretical arguments

The optimal isotope from theory is given by Eq. (5) , i.e. the one with the largest phase space and Coulomb correction combined with the largest nuclear matrix elements. The first quantity is the easiest to determine and histogramed in Fig. 4. As can be seen ^{150}Nd would come of best. The Coulomb correction supersedes even the phase space dependence of the Q-value (it scales with Q^5 for $0\nu\beta\beta$-decay), the latter would make ^{48}Ca the most suitable nuclide. A much more complicated statement involves the nuclear matrix elements. Their calculation is a severe challenge in nuclear structure physics. In contrast to the $2\nu\beta\beta$-decay which can be described by pure Gamow-Teller transitions through intermediate 1^+-states, the neutrinoless mode can also occur through other multipoles. Three different kinds of calculations are used, nuclear shell model calculations (NSM) [5], quasi-particle random phase approximations (QRPA) [6, 7] and the Interacting Boson Model (IBM) [8]. To support the calculations an experimental program was launched to provide as much input to the calculations as possible [9]. Two especially interesting reactions are charge exchange reactions via (d,^{2}He) and (^{3}He,t) and ft-value measurements of electron capture and beta decay of the intermediate nucleus. In the first type of reaction the cross section measurement under zero degrees is directly linked to the Gamow-Teller strength B_{GT} for 1^+-states. Summing their contribution should reproduce the observed $2\nu\beta\beta$-decay half-lives (Fig. 2). Already quite interesting nuclear structure features have been discovered, which might lead to a deeper understanding of the involved physics. First measurements under larger angles have been performed, which might reveal also contributions from higher multipoles, but the relation is not straightforward.

In general, various improvements have been achieved in recent years. The problem of short range correlation is much better understood now and nuclear deformation is about to be included in the matrix
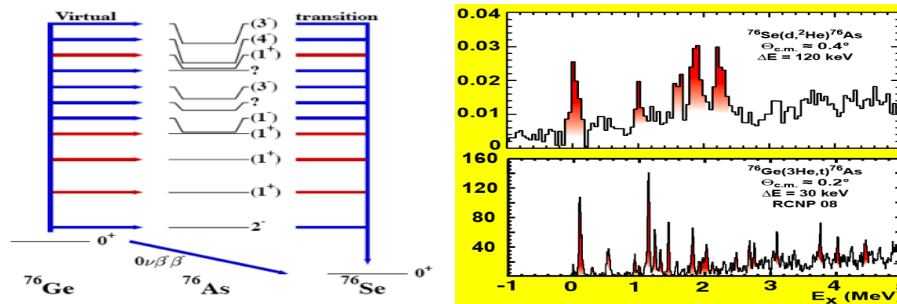
Fig. 2: Left: Schematic plot of the multipole transitions taking place in double beta decay, as an example ^{76}Ge is used. In $2\nu\beta\beta$-decay only the intermediate 1^+-states contribute while in the $0\nu\beta\beta$-decay decay all multipoles must be taken into account. Right: Measurement of 1^+-states as measured in charge exchange reactions at RCNP. Multiplying corresponding lines in both plots and summing up all pairs of line should result in the matrix element reproducing the $2\nu\beta\beta$-decay half-life (from [11]).

element calculations. Past calculations have been done always for spherical nuclei, first results from studies using deformation show that the general tendency is a reduction in the nuclear matrix elements and that not to absolute deformation matters, but the shape difference between the mother and daughter isotope. Deformation is especially important for ^{150}Nd as rare earth isotopes are strongly deformed. Additionally, it has been investigated that the errors in matrix element calculations can be be split into correlated and uncorrelated parts [10]. This is especially important when comparing different isotopes. For example, typically the quenching is included in the axial-vector constant g_A being part of the nuclear matrix element. It is often chosen to be either g_A=1 or 1.25. Obviously changing g_A from one value to another will have the same effect on all isotopes, thus it would not be correct to compare two nuclides by using the highest matrix element for one and the lowest for the other.

3 Background

Definetly the major experimental effort goes in the reduction of background, i.e. events depositing the same energy in a detector as $0\nu\beta\beta$-decay . Of course the aim is to get this as low as possible to take advantage of being "background free" (first formula in Eq. (3)). In this case the half-life sensitivity scales linearly with measuring time. Current best background levels achieved are in the order of about 0.1 counts/keV/kg/yr in the $0\nu\beta\beta$-decay peak range, which is already quite an achievement. However, if the claimed evidence in ^{76}Ge turns out to be wrong then the next benchmark is given by the hierarchical neutrino mass models and oscillation parameters, ie. neutrino masses of about 50 meV. This will require an improvement by 1-2 orders of magnitude in background. The background components can differ from experiment to experiment, but the typical components are

- The natural radioactive decay chains of U, Th including Rn in the air
- Radioisotopes produced by spallation processes of cosmic rays while materials were on the surface
- Neutron reactions underground produced by fission (α, n) or muon interactions in the rock
- Muons itself
- Potentially ^{40}K as long living isotope
- The $2\nu\beta\beta$-decay

One potential benefit is working with an isotope which has a Q-value above 2.614 MeV, which is the energy of the highest γ-line occuring in the natural decay chains (from ^{208}Tl decay). This implies already 1-2 order of magnitude lower background to start with and six isotopes are in this preferred range. Material selection is obviously one of the most important but time consuming activities for every
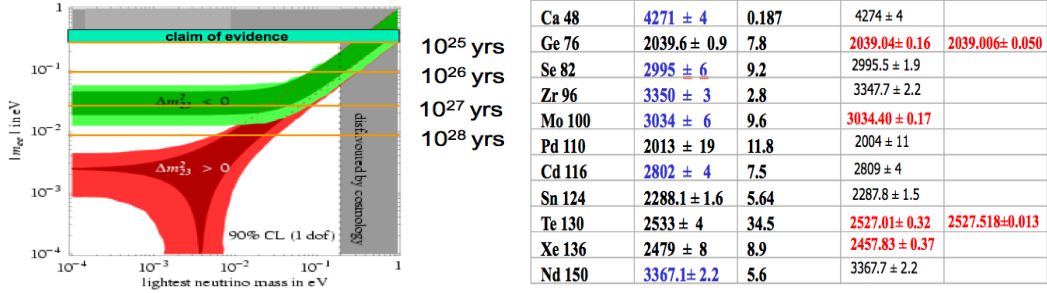
Fig. 3: Left: Schematic plot of the expected effective Majorana mass as a function of the lightest neutrino mass. Shown is the range of the evidence and the two hierarchical models. For comparison rough half-life ranges are given. Right: Double beta emitters with a Q-value of at least 2 MeV. The second column is the Q-value according to [4], the numbers beyond 2.614 MeV do not suffer from gammas of the natural decay chain. The third column reflects the natural abundance of the isotope and the last two columns show new Q-values either from the latest atomic mass evaluation [12] or as measured with Penning traps.

experiment. For the next generation contamination levels in the region down to μBq/kg must be achieved, which requires technologies to measure such small values. One idea is to electroform copper, a material used in almost all experiments, underground to avoid cosmogenic production of ^{60}Co. Apart from this purely passive methods in minimising impurities in all used materials also new ideas exist to actively reject background events. This might include pulse shape analysis to discriminate single site events (like double beta decay) from multiple site events, tagging the daughter ion created in the double beta decay in addition to the electrons or aiming for particle identification by using tracking detectors. A good example here is COBRA, planning to use pixelated CdZnTe semiconductors for this issue. As can be seen in Fig. 3 a clear discrimination between α's, β's and muons will be possible.

4 Energy resolution

Another important item is energy resolution. The few expected double beta decay events should be piling up at the Q-value and not be distributed to widely. This is even true if there is no external background due to the irreducible component of $2\nu\beta\beta$-decay . As the measured half-lives of $2\nu\beta\beta$-decay are typically several orders of magnitude smaller than the expected one for $0\nu\beta\beta$-decay , thus the fraction of $2\nu\beta\beta$-decay in the peak range has to be as small as possible which is directly linked to energy resolution. In this respect, semiconductor detectors, especially Ge-diodes, and cryogenic bolometers are leading.

5 Source mass

Another crucial item is the used mass, as it determines the source strength. Already with the achieved results currently it is obvious that future experiments have to use isotopically enriched material. As can be seen in Eq. (3) even in the background limited case the half-life sensitivity will depend linearly on this quantity. The process of enriching several hundred kilograms of isotopes is quite expensive and currently dominantly done in Russia using ultracentrifuges. Recently, to option of ion cyclotron resonance (ICR) has been explored in some detail. Its advantage would be its flexibility to enrich various materials. Also the more isotope specific atomic vapour laser ionisation spectroscopy (AVLIS) could be used. From the financial point of view noble gases are the cheapest to enrich, thus favouring ^{136}Xe as a good isotope.

## 6 Disentangling the physics process

If a peak at the Q-value of the transition indeed will be observed, various issues will show up before extracting a neutrino mass. The first thing is to probe whether it is really double beta decay and not some
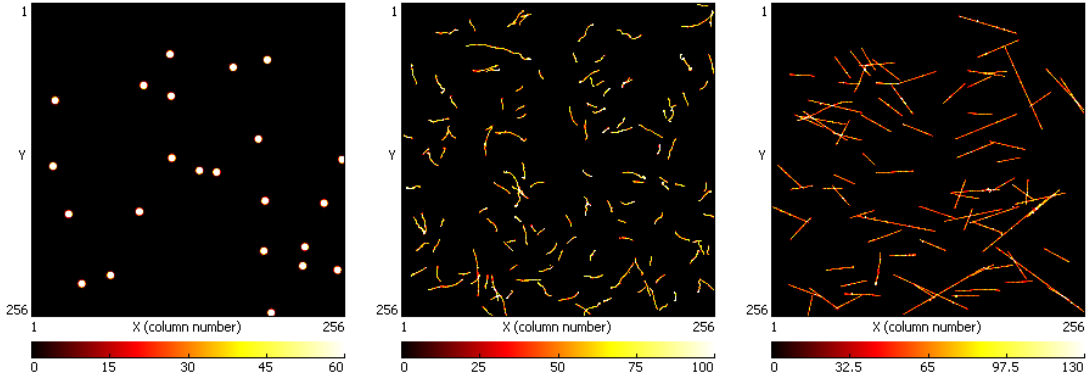
Fig. 4: Preselected sample of alpha (left) and beta particles (middle) as well as muons (right) obtained by COBRA with a 55μm pixel detector. Evident is the particle identification and the potential tracking option.

potential background component. The obvious thing to do is using another isotope. Fig. 5 combined with certain assumptions on the nuclear matrix elements predict a certain half-life region. The likelihood that at a different energy in another isotope a background component will produce the same peak with the correct half-life ratio is very small. If really established that there is a neutrinoless double beta peak, the question will arise about the underlying physics process. There are various Beyond the Standard Model processes which would allow for $\Delta L = 2$ processes like right-handed weak currents (V+A interactions), R-parity violating SUSY (the interesting parameter here is λ'_{111}), double charged Higgs-bosons and Kaluza-Klein excitations, just to mention a few. However, the Schechter-Valle theorem [1] guarantees that neutrinos are Majorana particles because at some level of perturbation theory it is always possible to draw a Feynman diagram for a Majorana mass, but the contribution to $0\nu\beta\beta$-decay is not known. Most of the new particles predicted in the TeV range hardly change any experimental observable in double beta decay and therefore constraints of other searches like at the LHC become important to rule out these options. Two mechanisms, namely KK-excitations and V+A interactions, might be directly testable. Recently it has been shown that the nuclear matrix elements show a sensitivity to KK-excitations and thus by comparing different measured isotopes it might be possible to extract information on that [?]. Quite a big effect might be caused by V+A interactions. The single electron energy spectrum and also the opening angle between the two emitted electrons is completely different compared to the neutrino mass mechanism, it has been shown that an alternative process like β^+/EC has an enhanced sensitivity to V+A interactions [14] and also $0^+ \rightarrow 2^+$ should be dominated by this process. By taking recoil effects into account the latter process might not be a good candidate for discrimination anymore [15]. The process of β^+/EC would require completely new isotopes to be considered, like ^{106}Cd. An advantage will be the experimental signature of two 511 keV photons combined with characteristic X-rays, a disadvantage is that the available transition energy is only $Q - 2m_ec^2$ because of the positron creation. The first mentioned process to discrimate neutrino mass and V+A interactions would require to measure single electron energy spectra and their opening angle, i.e. a detector with tracking capabilities. Currently only three options of this kind are discussed, foils of enriched material in a large number of TPCs (SuperNEMO), filling enriched ^{136}Xe in a gas TPC (EXO) and high resolution pixelated CdZnTe semiconductor detectors (COBRA).

From all the above mentioned arguments including the uncertainties in the nuclear matrix elements it becomes apparent that we have to investigate $0\nu\beta\beta$-decay in at least 3-4 isotopes to be able to extract a reliable neutrino mass value.
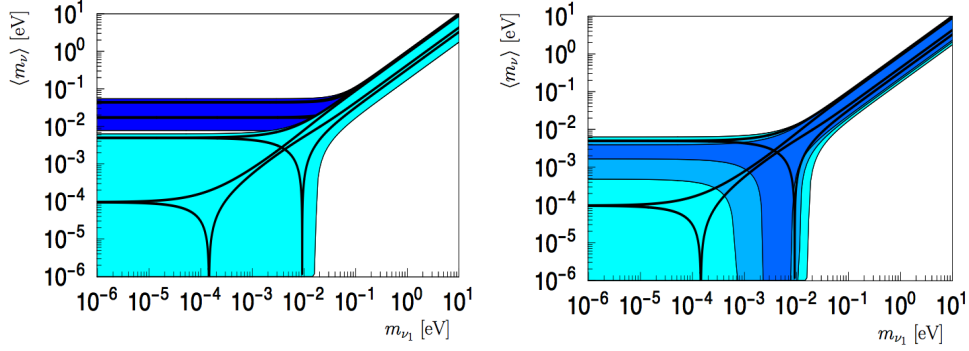
Fig. 5: Left: Effective Majorana mass as a function of the lightest neutrino mass eigenstate. Within the given intervalls of oscillation parameters over a wide range a cancellation in the normal hierarchy can be seen, while the inverted hierarchy has a lower bound due to the non-maximal mixing of solar neutrinos. Right: The region of cancellations shrinks significantly if the value of $\sin^2_{13}$ can be restricted to be less than 0.051, 0.025 and 0.0051 respectively. Thus, the next generation of reactor experiments and superbeams will help a lot. For both plots, the other parameters are fixed to be $\Delta m^2_{23} = 1.4 - 3.3 \times 10^{-3} eV^2$, $\Delta m^2_{12} = 7.2 - 9.1 \times 10^{-5} eV^2$ and $\sin^2 2\theta_{12} = 0.23$-$0.38$. Nuclear matrix element uncertainties are not included in the plot (from [16]).

7 Impact of other neutrino measurements

Neutrinoless double beta decay is not the only neutrino physics process and thus can be linked with other mass measurements onx oscillation results. Rewriting Eq. (6) in terms of oscillation parameters results in

$$\langle m_{\nu_e} \rangle = \cos^2_{12} \cos^2_{13} m_1 + \sin^2_{12} \cos^2_{13} e^{i\alpha} \sqrt{m_1^2 + \Delta m^2_{12}} + \sin^2_{13} e^{i\beta} \sqrt{m_1^2 + \Delta m^2_{12} + \Delta m^2_{23}} \quad (7)$$

Thus, the actual predicted value of $\langle m_{\nu_e} \rangle$ also depends on an accurate knowledge of oscillation parameters. For example, assuming CP-invariance (i.e. the complex phases will be ± 1) and $\sin^2_{13} = 0$ can lead to a complete cancellation in the normal hierarchy scenario if $| \tan\theta_{12} |= m_1/m_2$. An even wider range of cancellations is possible if the current upper bound on $\sin^2_{13}$ is taken. In the inverted scheme this is not possible as there is a lower limit due to the non-maximal value of θ_{12}. Both facts are shown as an example in Fig. 5.

Furthermore, cosmology provides bounds on the sum of the neutrino masses $\sum m_i$ and beta decay endpoint measurements depend on

$$m_\nu^2 = \cos^2_{12} \cos^2_{13} m_1^2 + \sin^2_{12} \cos^2_{13} m_2^2 + \sin^2_{13} m_3^2 \quad (8)$$

independent of the character of the neutrino. All this various measurements will constrain the allowed parameter range for neutrino mass and will hopefully lead to a coherent picture by the end of the day.

8 Conclusion

The observation of $0\nu\beta\beta$-decay would be a striking new step beyond the Standard Model and prove that neutrinos are their own antiparticles. The next 5 years will set the scene for the long term prospects in the field. In this report the options and critical quantities are discussed in detail not focussing on any specific experiment. As became apparent there is no unique preferred isotope to use for the potentially most sensitive search. Actually, due to the various physics processes possible for total lepton number violation and the uncertainties in nuclear matrix element calculations it is rather mandatory to measure at least 3-4 different isotopes.

References

[1] Schechter J and Valle J W F *Phys. Rev.* D **25** 2591 (1982)

[2] Cremonesi O , these proceedings

[3] Klapdor-Kleingrothaus H V et al. *Phys. Lett.* B **586** 198 (2004)

[4] Boehm F, Vogel P , Physics of massive neutrinos, Cambridge University Press 1992

[5] Caurier E et al. *Phys. Rev. Lett.* **100** 052503 (2008)

[6] Simkovic F et al. *Phys. Rev.* C **79** 055501 (2009)

[7] Kortelainen M, Civitarese O, Suhonen J *Phys. Lett.* B **647** 128 (2007)

[8] Barea J and Iachello F *Phys. Rev.* C **79** 044301 (2009)

[9] Zuber K , nucl-ex/0511009

[10] Faessler A et al., *Phys. Rev.* C **79** 053001 (2009)

[11] Frekers D, Talk presented at MEDEX 09, Prague

[12] Audi G, Wapstra A H and Thibault C *Nucl. Phys.* A **729** 337 (2003)

[13] Deppisch F, Päs H *Phys. Rev. Lett.* **98** 232501 (2007)

[14] Hirsch M et al. *Z. Phys.* A **347** 151 (1994)

[15] Tomoda T *Phys. Lett.* B **474** 245 (2000)

[16] Hirsch M , Talk presented at Neutrino 2006 conference, Santa Fe