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Neutrinoless double beta decay

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Abstract. The physics potential of neutrinoless double beta decay is discussed. Furthermore, experimental considerations as well as the current status of experiments are presented. Finally, an outlook towards the future, work on nuclear matrix elements and alternative processes is given.

Keywords. Double beta decay; neutrino mass; beyond Standard Model physics.

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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 being confirmed by long baseline accelerator experiments and the solution of the solar neutrino problem being confirmed by nuclear reactors. All can be explained by neutrino oscillations, which are depending on mass differences $\Delta m_{ij}^2 = m_j^2 - m_i^2$ assuming a two-flavour mixing only. The determination of absolute neutrino masses is now a major issue, because neutrino oscillation experiments do not allow to determine this. The classical way to search for the rest mass of the neutrino is to study the end-point 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 mass 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. Another laboratory process is the rare nuclear decay of neutrinoless double beta decay typically leading to sub-eV values as well.

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

Single beta decay must be forbidden or at least strongly suppressed to observe this decay and 35 potential isotopes exist in nature. As can be seen from eq. (1), the given decay mode violates 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 ϵ via

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{\rm PS}|M_{\rm Nuc}|^2\,\epsilon^2, \quad (2)$$

where $G_{\rm PS}$ is the phase space, $|M_{\rm Nuc}|$ is the involved nuclear matrix element for the physics process considered to describe this decay and ϵ is the quantity of interest. Various BSM processes such as light and heavy Majorana neutrino exchange, right-handed weak currents, R-parity violating SUSY (λ'_{111}) and double charged Higgs bosons can be considered. If $0\nu\beta\beta$-decay is ever observed, this would imply that neutrinos are Majorana particles [2]. However, given all the possible processes, the important question is 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 of 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 [3]. For a recent extensive review on the particle physics in double decay, see [4].

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

$$\epsilon \equiv \langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|, \quad (3)$$

where U^2_{ei} are the 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. (3) 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

$$U = U_{PMNS}(\theta_{12}, \theta_{13}, \theta_{23}, \mathrm{e}^{i\delta}) \times \mathrm{diag}(1, \mathrm{e}^{i\alpha}, \mathrm{e}^{i\beta}) \quad (4)$$

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

$$\langle m_{ee}\rangle = |m^1_e| + |m^2_e|\mathrm{e}^{2i\alpha} + |m^3_e|\mathrm{e}^{2i\beta} \quad (5)$$

with the individual contributions given as

$$\begin{aligned} m^1_e &= |U_{e1}|^2\, m_1 = m_1 \cos^2\theta_{12}\cos^2\theta_{13},\\ m^2_e &= |U_{e2}|^2\, m_2 = m_2 \sin^2\theta_{12}\cos^2\theta_{13},\\ m^3_e &= |U_{e3}|^2\, m_3 = m_3 \sin^2\theta_{13}. \end{aligned} \quad (6)$$

Latest global fits to available oscillation parameters are given in [5,6]. New important ingredients are that 3-flavour fits to solar neutrinos [7], observations from T2K [8] and MINOS [9] as well as new reactor neutrino data by Double Chooz, Daya Bay and RENO proving [10] a non-zero value of θ_{13}. As the oscillations do not fit the absolute scale there are two options for arranging the mass eigenstates, either $m_3 > m_2 > m_1$ (normal hierarchy, NH) or $m_2 > m_1 > m_3$ (inverse hierarchy, IH). If the neutrino masses turn out to be close to the current limit from beta decay there is a quasidegeneracy ($m_1 \approx m_2 \approx m_3 \equiv m_0$). In case of hierarchies the two larger masses can be expressed as

$$m_2 = \sqrt{m_1^2 + \Delta m_\odot^2}, \qquad m_3 = \sqrt{m_1^2 + \Delta m_{\text{atm}}^2} \qquad \text{(normal)}$$

$$m_2 = \sqrt{m_3^2 + \Delta m_\odot^2 + \Delta m_{\text{atm}}^2}, \qquad m_1 = \sqrt{m_3^2 + \Delta m_{\text{atm}}^2} \qquad \text{(inverted)} \tag{7}$$

with the solar splitting $\Delta m_\odot^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5}$ eV^2 and the atmospheric splitting $\Delta m_{\text{atm}}^2 = 2.49 \pm 0.09 \times 10^{-3}$ eV^2 (normal), $\Delta m_{\text{atm}}^2 = -2.343^{+0.10}_{-0.09} \times 10^{-3}$ eV^2 (inverted) [5]. The principal behaviour of $\langle m_{ee} \rangle$ as a function of the lightest mass eigenstate is shown in figure 1 for a value of $\sin^2 2\theta_{13} = 0.02$ and the dependence of individual parts on the parameters. For $\langle m_{ee} \rangle$ values larger than about 100 meV, neutrinos are almost degenerate, the inverted hierarchy covers a range of about 10–50 meV and below 10 meV is the region of the normal hierarchy. As can be seen, in the NH there can be a cancellation among the terms, the allowed region for that becomes larger with increasing $\sin^2 2\theta_{13}$. There is no such effect in the IH because of the non-maximal solar mixing angle θ_{12}. In addition, the gap between the two bands in the hierarchical region will shrink with increasing $\sin^2 2\theta_{13}$.

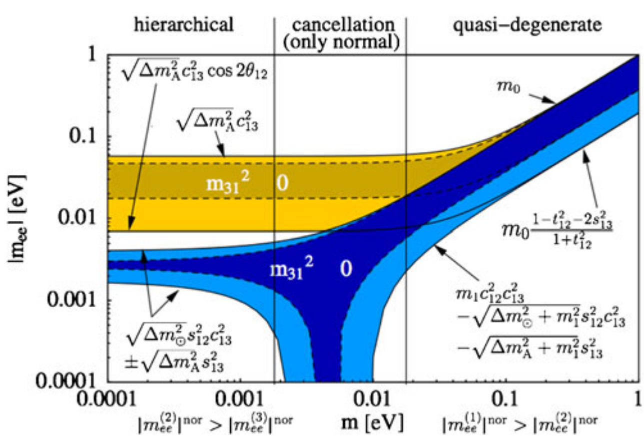

Figure 1. A plot of the effective Majorana neutrino mass $\langle m_{ee} \rangle$ as a function of the smallest neutrino mass as introduced by [11]. For illustration the principal dependences of individual features on the oscillation parameters are shown. A value of $\sin^2 2\theta_{13} = 0.02$ has been assumed, furthermore $t_{12}^2 = \tan^2 \theta_{12}$. Uncertainties introduced due to the involved nuclear matrix elements are not included (from [12]).

Half-lives for the IH are in the region beyond 10^{26} yr while half-lives in the NH are well beyond 10^{28} yr.

3. General experimental considerations

Evidently, measurements of half-lives well beyond 10^{25} yr are by no means trivial. As signal for the process given in eq. (1) serves a peak in the sum energy spectrum of the two electrons equivalent to the Q-value of the nuclear transition. The corresponding half-life in case of no background is given by the radioactive decay law

$$T_{1/2}^{0\nu} = \frac{\ln 2 m a t N_{\mathrm{A}}}{N_{\beta\beta}}, \tag{8}$$

where m is the used mass, a the isotopical 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 (i.e. all potential energy depositions in the region of interest, i.e. around the Q-value, not being neutrinoless double beta decay) is assumed scaling linearly with time, the half-life sensitivity can be estimated as

$$T_{1/2}^{0\nu} \propto a \times \epsilon \sqrt{\frac{M \times t}{B \times \Delta E}}, \tag{9}$$

where ϵ is the efficiency for detecting the total energy of both electrons, ΔE is the energy resolution at the peak position and B is the background index normally given in counts/keV/kg/yr. 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. Furthermore, the energy resolution [12a] 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

$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta\text{-decay}). \tag{10}$$

Here again energy resolution matters, because of the continuous spectrum of the $2\nu\beta\beta$-decay mode, its high energy part leaks into the peak region (see figure 2). Nevertheless, this can be a worry as the half-life is typically several orders of magnitude smaller 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 some important numbers in table 1.

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 the form of TPCs containing thin foils of double beta emitters. Here single electron spectra and opening angles can be measured as well.

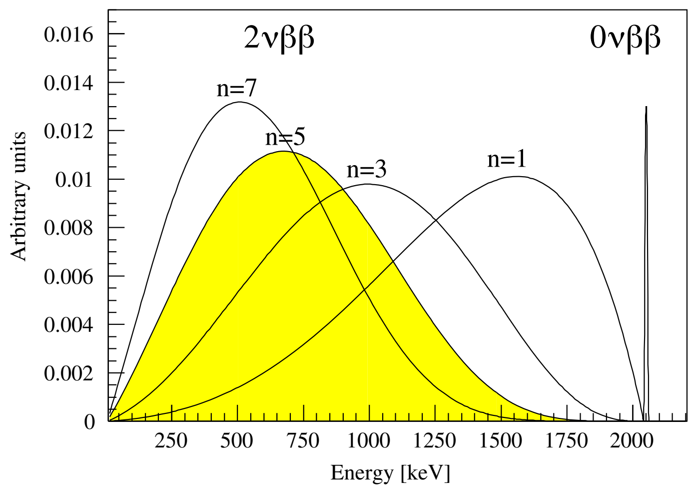

Figure 2. Schematic plot of the sum energy spectrum of the two electrons in double beta decay. $0\nu\beta\beta$-decay results in a peak at the Q-value of the transition. Various modes can be characterized by the phase-space dependence $(Q - E)^n$. The mode $n = 5$ is the $2\nu\beta\beta$-decay (yellow)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

Table 1. Table showing the eleven candidate isotopes with a Q-value larger than 2 MeV. Given are the natural abundances, Q-values as determined from precise Penning trap measurements (those with sub-keV errors) or from the atomic mass evaluation 2003 [13], the measured averaged $2\nu\beta\beta$-decay half-lives as recommended in [14] plus the recent measurement of ^{136}Xe [15,24]. The last column shows the experiments addressing the measurement of the corresponding isotope. For some experiments, only the 'default' isotope is mentioned as they have the option of exploring several ones. Several additional research and development projects are ongoing.

Isotope	Nat. Abund. (%)	Q-value (keV)	$T_{1/2}^{2\nu}$ (10^{20}/yr)	Experiment
^{48}Ca	0.187	4272 ± 4	$0.44^{+0.06}_{-0.05}$	CANDLES
^{76}Ge	7.8	2039.006 ± 0.050	15 ± 1	GERDA, MAJORANA
^{82}Se	9.2	2995.5 ± 1.9	0.92 ± 0.07	SuperNEMO, LUCIFER
^{96}Zr	2.8	3347.7 ± 2.2	0.23 ± 0.02	–
^{100}Mo	9.6	3034.40 ± 0.17	0.071 ± 0.004	AMoRE
^{110}Pd	11.8	2017.85 ± 0.64	–	–
^{116}Cd	7.5	2813.50 ± 0.13	0.28 ± 0.02	COBRA, $CdWO_4$
^{124}Sn	5.64	2287.8 ± 1.5	–	–
^{130}Te	34.5	2527.518 ± 0.013	$6.8^{+1.2}_{-1.1}$	CUORE
^{136}Xe	8.9	2457.83 ± 0.37	21.1 ± 2.5	EXO, NEXT
			23.8 ± 1.6	KamLAND-Zen
^{150}Nd	5.6	3371.38 ± 0.20	0.082 ± 0.009	SNO+, MCT

4. Experimental status

Three different goals are considered for future investigation depending on the outcome of the individual steps. The first one is to probe the claimed observation of $0\nu\beta\beta$-decay in ^{76}Ge with a half-life of $2.23 \pm 0.04 \times 10^{25}$ yr [17,18]. If this is confirmed, the next generation will collect sufficient statistics for a precision half-life measurement. It might be even possible to perform an intrinsic consistency check by also looking at the $0\nu\beta\beta$-decay into the first excited state [19]. Furthermore, due to the 'multi-isotope' approach an observation in one isotope predicts a half-life for the other ones by taking into account the uncertainties in nuclear matrix elements (see §6). Observing peaks at different positions in energies within the right range of half-lives excludes potential unrecognized backgrounds. Anyhow, the 'multi-isotope' ansatz is needed to compensate for matrix element uncertainties.

In case the evidence is not confirmed, the next goal must be the region of inverted hierarchy, i.e. $\langle m_{ee} \rangle$ below ≈50 meV. The neccessary half-life requirement to touch this region is given in [20]. As the requirements on mass and background for this purpose are already demanding, fully excluding the IH is more than challenging. If no signal is found in the IH, the final 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 neutrinos [21]. For that, half-lives well beyond 10^{28} yr have to be measured.

Currently the field is in transition towards the next generation of experiments. The year 2011 saw the start of four new double beta experiments, namely, GERDA (using ^{76}Ge), EXO and KamLAND-Zen (using ^{136}Xe) and CANDLES (using ^{48}Ca). GERDA [22] is a next-generation experiment based on Ge-semiconductors containing ^{76}Ge situated in the Gran Sasso Underground Laboratory (Italy). The idea is to run bare crystals within LAr which serves as shielding and cooling. In the 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 have been deployed and official data taking started on 1 November 2011. A spectrum from a commissioning run using three enriched detectors is shown in figure 3. As can be seen, the $2\nu\beta\beta$-decay contribution is already clearly visible. Currently, for a second phase, another 37.5 kg of enriched Ge is in the process of conversion into BEGe detectors. These point-contact detectors allow an optimized separation of single site energy depositions (like double beta decay) and multiple site interactions (most of the background like Compton scattering with an additional second interaction) by using pulse shape analysis [23].

Due to the relatively cheap enrichment of noble gases, two large-scale experiments based on enriched ^{136}Xe have started. First is EXO-200, using about 175 kg LXe in the form of a TPC located at WIPP (USA). The early data look very promising (figure 3) and a first half-life for the $2\nu\beta\beta$-decay of ^{136}Xe could be determined (see table 1). A unique option explored for the future would be the detection of the daughter ion which should result in major background reduction. 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

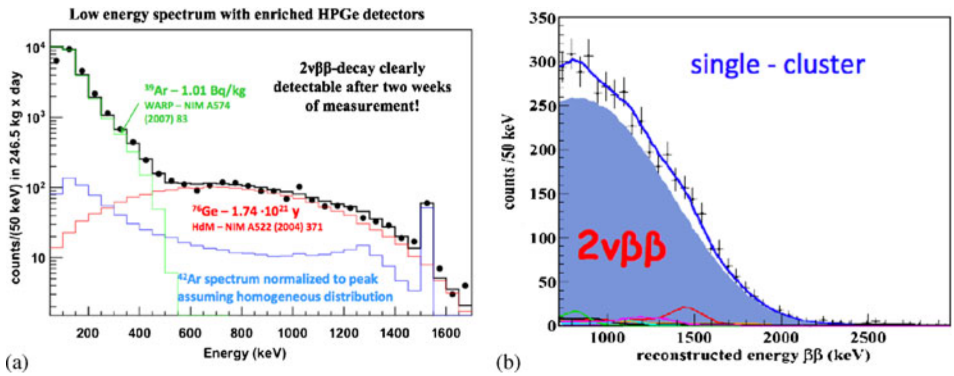

Figure 3. (**a**) Spectrum from a commissioning run of GERDA using three enriched Ge detectors. The three major visible components are ^{39}Ar-decay, a ^{42}K contribution due to ^{42}Ar decay and the $2\nu\beta\beta$-decay of ^{76}Ge. (**b**) Initial results of EXO-200 lead to a first discovery and half-life measurement of the $2\nu\beta\beta$-decay of ^{136}Xe being the dominant contribution to the spectrum (from [16], details can be found in [15]).

in the detector and data taking has started in September 2011. A $2\nu\beta\beta$-decay half-life of ^{136}Xe has been measured which is in agreement with EXO and a new lower half-life limit for the neutrinoless decay of 5.7×10^{24} yr (90% CL) is given [24].

Last but not least, there is CANDLES using 305 kg of CaF_2 scintillators, focussing on ^{48}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.

5. Future experiments and ideas

With the experiments mentioned in the previous session running, there will be more online in a few years time and additionally still interesting research and development is ongoing, a few of them are mentioned here (see table 1). From the semiconductor point of view, two more projects exist, MAJORANA and COBRA. MAJORANA is using Ge-detectors as GERDA and is considering to have up to 30 kg enriched detectors running by 2014 in the Sanford Underground Laboratory (USA). COBRA is exploring CdZnTe semiconductor for the search of ^{116}Cd. The detectors are much smaller than the typically used Ge diodes thus having a much higher granularity and discrimination against multisite events will be realized by multidetector events. Furthermore, for practical purposes it is convenient that these detectors will run at room temperature. A unique feature which is explored is pixelization which should allow massive background reduction by particle identification due to tracking. A prototype detector of about 0.5 kg is currently installed in the Gran Sasso Laboratory.

In a similar spirit as KamLAND-Zen another large-scale scintillator experiment is in the building-up phase. SNO+ aims to use in the first phase of operation (the second phase should be pure scintillator mainly for the study of solar neutrinos) 780 t of Nd-loaded scintillator for the search of ^{150}Nd decay. The default assumption is a 0.1% loading of the scintillator, resulting in 43 kg of ^{150}Nd, while an optimization of 0.3% loading is under investigation. ^{150}Nd has the second highest Q-value of all double beta isotopes (3371 keV) and is always among the theoretically most preferred isotopes. SNO+ is supposed to start in 2013. Other groups explore various solid-state scintillators, for example $CdWO_4$.

A different class of detectors not mentioned yet but with a lot of options are cryogenic bolometers. The most advanced approach is CUORE using 750 kg of TeO_2 crystals to search for the ^{130}Te decay. The benefit of using Te is its high natural abundance. This experiment is in the building-up phase at Gran Sasso Laboratory and is planned to start data taking with the full amount in 2014. Various other bolometers are currently explored like $CaMoO_4$ (AMoRE) and ZnSe (LUCIFER) to search for ^{100}Mo and ^{82}Se respectively.

Finally, tracking devices in the form of TPCs using the double beta emitter in the form of thin foils are explored. Due to the tracking it is possible to measure the individual electron energies and the opening angle between them. This might be important if $0\nu\beta\beta$-decay is discovered as the neutrino mass mechanism and right-handed weak current contribution differ significantly in these quantities. As the next step in a series of experiments, SuperNEMO is planning to use at least 100 kg of ^{82}Se in the form of 20 TPC modules with 5 kg source mass per module. The first demonstrator module is supposed to start data taking in 2014.

6. Nuclear matrix elements – Theory and experiment

The conversion of an observed half-life or its limit into $\langle m_{ee} \rangle$ requires the knowledge of the nuclear transition matrix elements, see eq. (2). Any uncertainty in the nuclear matrix element due to its square dependence results in a significant uncertainty in the deduced neutrino mass. This is another important argument for the multi-isotope approach. Various theoretical methods have been applied in the past, especially nuclear shell model (NSM) and quasirandom phase approximation (QRPA) calculations, which were recently joined by new methods like the interaction boson model (IBM) and energy density functional treatment (GCM). A compilation of the available calculations normalized to one value of r_0 and g_A is given in figure 4. As can be seen, there is quite some spread in the obtained values and uncertainties are not claimed for all methods.

As all double beta emitters are even–even nuclei, their ground-state transitions are characterized as $0^+ \rightarrow 0^+$ transitions. Given the fact that almost all $2\nu\beta\beta$-decay half-lives are known, the associated matrix element $M^{2\nu}$ can be deduced. However, these are pure Gamow–Teller transitions only mediated by the 1^+ states of the intermediate nucleus. The contributing transitions are restricted to less than 5 MeV and they contribute only a fraction to $M^{0\nu}$. In the latter case all levels up to about 100 MeV with all multipolarities can contribute. Furthermore, effects and treatment of short-range correlations become very important [25]. The matrix elements must be calculated separately for the individual processes discussed in §1. Thus, they contain information on the physics process involved as well [26–28]. Given the complexity of the problem and a lack of missing experimental

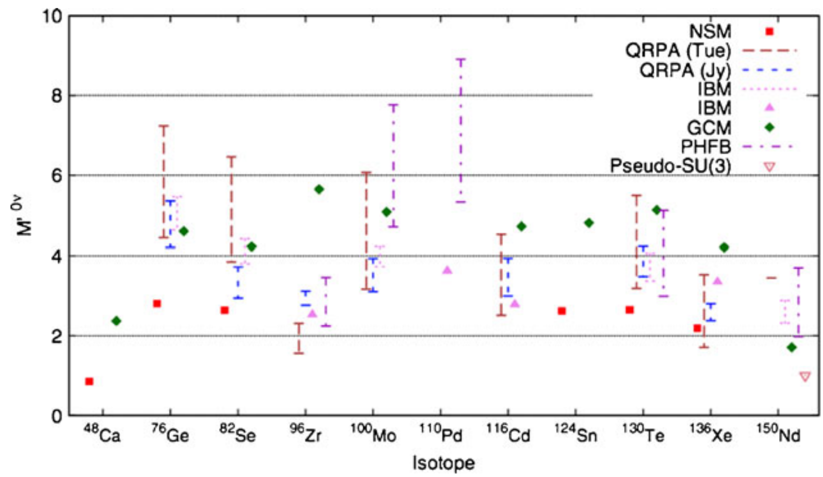

Figure 4. Compilation of nuclear matrix element calculations for the eleven relevant isotopes. Existing publications were used and normalized to a nucleon radius of $r_0 = 1.2$ fm and $g_A = 1.25$ (from [20]).

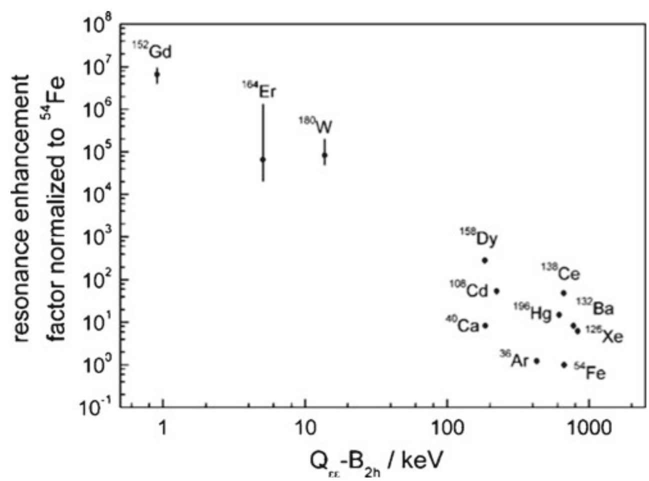

Figure 5. Resonance enhancement factor for neutrinoless EC/EC relative to ^{54}Fe based on precision mass spectrometry with Penning traps (from [33]).

information, a program was started to improve the situation from the experimental point [29]. Part of the program is precise Q-value determinations using Penning traps (see table 1), charge exchange reactions in the form of (^{3}He, t) and (d,^{2}He) reactions to determine the Gamow–Teller strength B_{GT} for the transitions to the intermediate 1^+-states and nucleon transfer reactions. This leads to new insights and refinements of the calculations.

7. 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). Three different variants are possible depending on the Q-value:

$$(Z, A) \rightarrow (Z-2, A) + 2e^+ (+2\nu_e) \quad (\beta^+\beta^+), \tag{11}$$

$$e_B^- + (Z, A) \rightarrow (Z-2, A) + e^+ (+2\nu_e) \quad (\beta^+/\text{EC}), \tag{12}$$

$$2e_B^- + (Z, A) \rightarrow (Z-2, A) (+2\nu_e) \quad (\text{EC}/\text{EC}). \tag{13}$$

$\beta^+\beta^+$ is always accompanied by EC/EC and β^+/EC-decay. The positron production reduces the effective Q-value by $2m_ec^2$ 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 γ-rays. It was shown that the β^+/EC-mode has an enhanced sensitivity to right-handed weak currents [30] 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 [31,32] 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 5) where such a scenario is realized [33]. 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 an order of magnitude longer making this method slightly less attractive.

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