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Neutrinoless Double Beta Decay

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Abstract. The search for neutrinoless double beta decay is the only practical way to test whether neutrinos are Majorana or Dirac particles. The next generation of experiments aim to probe the effective Majorana neutrino mass down to few 10 meV, as predicted by oscillation experiments in case of the inverse mass hierarchy. According to recent nuclear matrix calculations, the predicted decay rates per mass of double beta isotope are varying within a factor of few when comparing them within the same theoretical model framework. The sensitivity of the upcoming experiments depend therefore primarily on the available mass of double beta isotopes and the experimental conditions. In particular, the achievable background suppression and the detection efficiency will be decisive for their success.

1. Introduction

The search for neutrinoless double beta decay is a central research topic in fundamental physics. Excellent review articles are available at [1] and in the references therein. Detailed reports on the ongoing experimental and theoretical activities have been given at this conference and are part of this conference proceedings. This paper will first give an introduction to neutrinless double beta decay which has been adapted from our recent Aspera roadmap paper [2], then focus on the question whether current nuclear matrix element calculations favor one double beta isotope over an other one, subsequently give a brief overview on the current experimental projects and their time lines, and conclude with a short summary on the experimental road map. Different to the oral presentation, I will not discuss here details of the experimental projects, as the interested reader can find this in much more detail in the dedicated articles in this proceedings.

2. The physics case

The discovery of neutrino oscillations in solar and atmospheric neutrino experiments have established neutrinos as particles with non-zero rest mass. Long-baseline experiments with neutrinos from nuclear power reactors and accelerators have confirmed these findings and, in conjunction with solar and atmospheric neutrino experiments, provide precision data and constraints on the mass differences and mixing angles. Neutrino masses and mixing are commonly considered as the first manifestation of physics beyond the Standard Model of electroweak interaction.

The central questions today in neutrino physics concern the nature of the neutrino particle (Dirac of Majorana), the absolute mass scale, the mixing angle θ_{13} and the CP violation in the leptonic sector. Establishing whether neutrinos are Dirac fermions and therefore different from their antiparticle, or Majorana fermions and therefore identical to their antiparticles, is of paramount importance for understanding the underlying symmetries of particle interactions and the origin of ν masses.

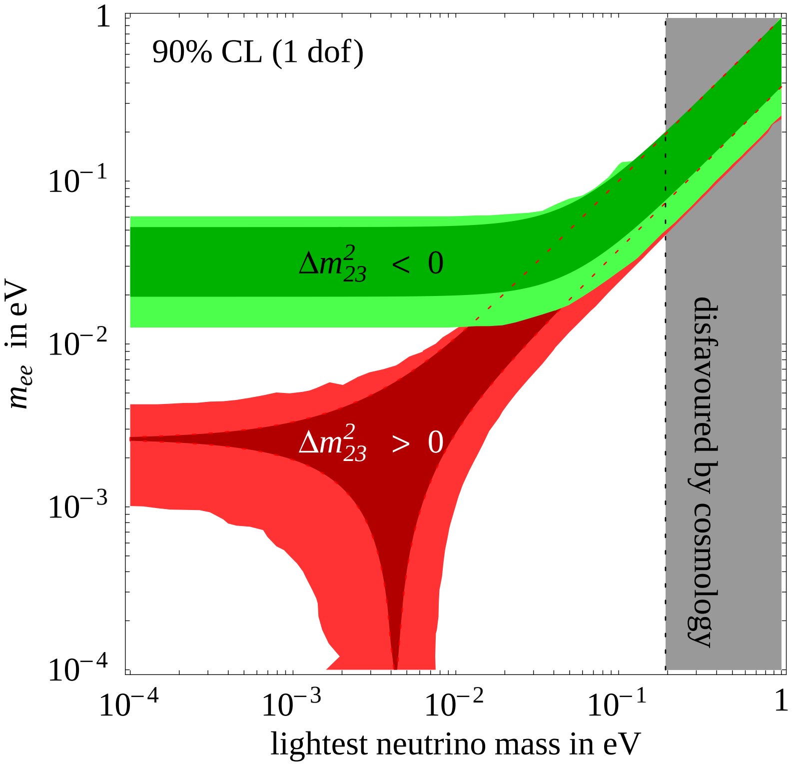

Figure 1. Allowed effective neutrino mass vs. mass of the lightest mass state predicted by neutrino oscillation experiments [3].

The only practical way to test whether neutrinos are Majorana particles is to search for the neutrinoless double beta decay ($0\nu\beta\beta$). The neutrinoless double beta decay of a nucleus consists of the simultaneous transition of two neutrons into two protons with the emission of two electrons: (A,Z) $\rightarrow$ (A,Z+2) + e^- + e^-. This process is forbidden in the Standard Model because it violates lepton number conservation ($\Delta L = 2$). The experimental signature of this decay is a peak in the distribution of the electron sum energy at the transition energy. On the contrary, a continuous spectrum extending from 0 to the transition energy is observed for the allowed 2nd order process of the electroweak interaction: (A,Z) $\rightarrow$ (A,Z+2) + e_1^- + e_2^- + $\bar{\nu}_1$ + $\bar{\nu}_2$. The latter decay mode has been measured for several nuclei.

There are several possible mechanisms leading to the $0\nu\beta\beta$ process: exchange of a light neutrino, right-handed weak currents, exchange of super-symmetric particles, and other non-standard interactions. Independent of the leading term, the observation of $0\nu\beta\beta$ decay would unambiguously establish the Majorana nature of neutrinos. Once the $0\nu\beta\beta$ decay has been observed experimentally, the nature of the leading term could be studied by measuring the energy and angular distribution of the single electrons, by the branching ratios of $0\nu\beta\beta$ decays to excited levels, and by comparison of the decay rates of different nuclei.

In the case of light neutrino exchange, the expression of the half-life depends on the effective neutrino mass: $[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\langle m_\nu\rangle^2$, where $G^{0\nu}$ is a calculable phase space factor and $M^{0\nu}$ is the nuclear matrix element (NME) of the process. $\langle m_\nu\rangle =$

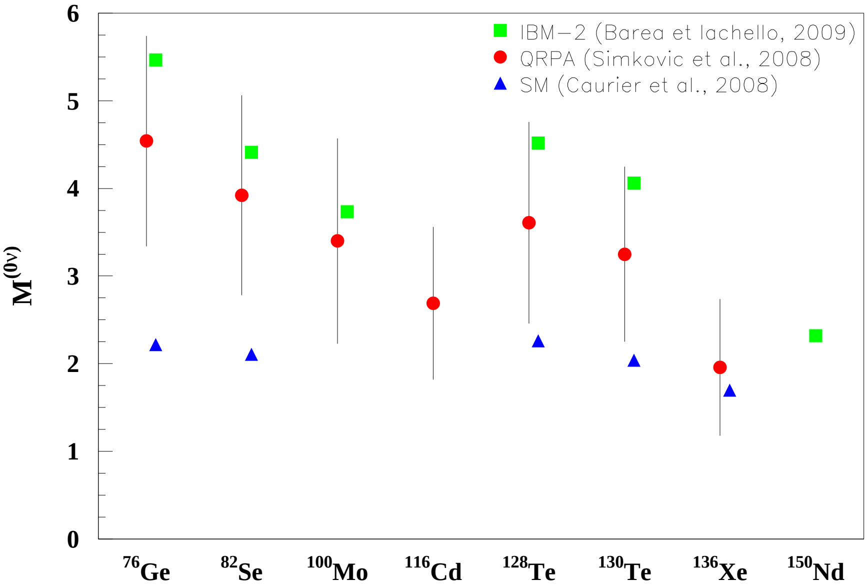

Figure 2. Compilation of three recent nuclear matrix element ($M^{(0\nu)}$) calculations for neutrinoless double beta decay [4, 6, 7].

$||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_1}||U_{e3}|^2 m_3 e^{i\phi_2}$ is the effective Majorana neutrino mass, m_1, m_2, m_3 are the masses related to the three neutrino mass eigenstates, U_{e1}, U_{e2}, U_{e3} are the elements of the first row of the neutrino mixing matrix and ϕ_1, ϕ_2 are the Majorana CP phases (± 1 if CP is conserved).

Fig. 1 summarizes the sensitivity required on $\langle m_\nu \rangle$ to determine the neutrino mass scheme. The present experiments with about 10 kg of double beta isotopes are sensitive to the quasi degenerate mass scheme ($\mathrm{m}_1 \cong \mathrm{m}_2 \cong \mathrm{m}_3$). The next generation of experiments, with approximately 100 kg of isotopes, will explore part of the mass range predicted by the inverted hierarchy ($\mathrm{m}_1 > \mathrm{m}_2 \gg \mathrm{m}_3$). These experiments will as well serve as bench tests for the following one ton scale experiments which are required to explore completely the inverted mass hierarchy. The meV mass range, predicted by the normal hierarchy ($\mathrm{m}_1 \ll \mathrm{m}_2 < \mathrm{m}_3$), is beyond the reach of the current technologies.

3. Comparison of decay rates of double beta decay isotopes

Central to the comparison of isotopes are the values of the nuclear matrix elements. Recent calculation using quasi-particle random phase approximations (Q)RPA [4, 5] and interacting Boson model (IBM-2) [6] show reasonable agreements, while shell model (SM) [7] calculations show discrepancies of about a factor of two, apart for ^{136}Xe. Recently, the authors of [8] pointed out that the discrepancy in ^{76}Ge is reduced when the wave functions are constrained to reproduce the experimental occupancies of the two nuclei involved in the transition. Fig. 5 displays the values of nuclear matrix elements taken from [4, 6, 7]. It should be noted that different nuclear radii have been used by the authors to evaluate the NME [9] which requires a (not included) rescaling for comparison. To illustrate how the different factors influence the overall decay rate per kg of isotopes for a given neutrino mass, the factors normalized to the respective ones from

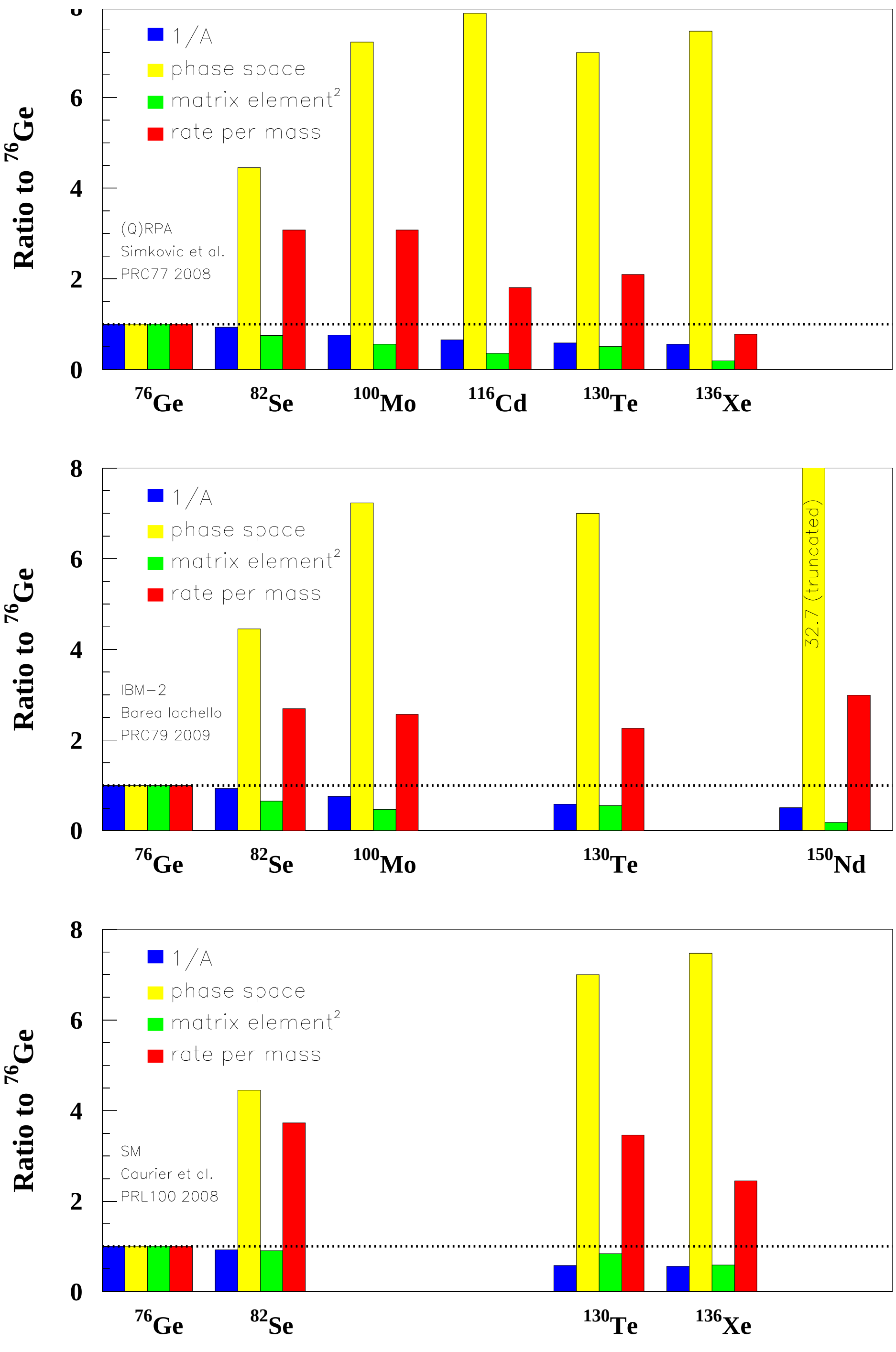

Figure 3. Comparison of the specific decay rates of double beta decay isotopes for a given effective neutrino mass are shown for three recent nuclear matrix element calculations: QRPA (top), IBM-2 (middle), SM (bottom). The contributing quantities ($1/A$, A: atomic number, phase space factor, (squared) nuclear matrix element) and the decay rates per mass are normalized to those of ^{76}Ge.

^{76}Ge are displayed in Fig. 3. A re-scaling because of different nuclear radii is not required in this normalized representation.

It is noteworthy, that the decay rates per unit mass of isotopes vary within less than a factor of four when comparing them within the same theoretical framework. The absolute decay rates of ^{76}Ge for a 50 meV effective neutrino mass and per ton×year of exposure are 9.1 ([4]), 13.2 ([6]), and 2.2 ([7]) which have a stronger spread than the scatter between the different nuclei within one theoretical model. As mentioned above, recent calculations for ^{76}Ge NME taking into account the accupancies of the involved nuclei increases the SM and reduces the QRPA values, thus reducing the tension amongst the two theoretical approaches [8].

The current status of nuclear matrix element calculations do not favor a particular isotope over an other because the decay rates per mass of isotopes scatter only within a factor of four within a theoretical framework. Experimental consideration as detection efficiency and background suppression will determine the final sensitivity of the different experimental approaches.

Name	Nucleus	Mass*	Method	Location	Time line
Running & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Experiments with construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48		scintillation	Solotvina	
COBRA	Cd-116, Te-130		ionization	LNGS	
DCBA	Nd-150		drift chamber	Kamioka	
EXO gas	Xe-136		gas TPC	SNOlab	
MOON	Mo-100		tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

Figure 4. Summary of experimental projects, type and mass of isotopes (not including detection and analysis efficiencies), experimental method, financial status, location and planned year of start-up.

4. Experimental projects

An overview of the experimental projects are given in Fig. 4. The masses of isotopes listed do neither include detection nor analysis efficiencies. They can range from e.g. 18% for the NEMO-3 up to 90% for GERDA or Cuore experiments. Essential to achieve the intended sensitivities of the different experiments is to operate the experiments free of background within the envisioned exposure. How to achieve this goal is central to the different experiments and the interested reader is referred to the respective articles in this conference proceeding. The first of the next generation experiments to become operational are GERDA at LNGS, Italy and EXO at WIPP, USA. Both plan to start their detector commissioning phase in 2009. Not included in this table is the recent project to load ^{136}Xe into a liquid scintillator in the KamLAND detector.

5. The future strategy

The future development of the field will strongly depend on the results of the upcoming GERDA [11] and EXO [12] experiments. If neutrinoless double beta decay is observed at the 1 eV scale, as claimed by part of the Heidelberg Moscow experiment [10], the decay could be studied with high precision with many different isotopes and different techniques. The effective mass could be measured with accuracy and the leading term governing the decay mode identified. In case that the claim is refuted, at least two experiments with about one ton of isotopes and zero background in the region of interest for several year×ton of exposure are required to cover the full mass range down to 10 meV predicted by oscillation experiments for the inverse mass hierarchy. Yet, there is no experimental concept how to explore the mass range down to 1 meV which is expected, if the normal mass hierarchy was realized by nature.

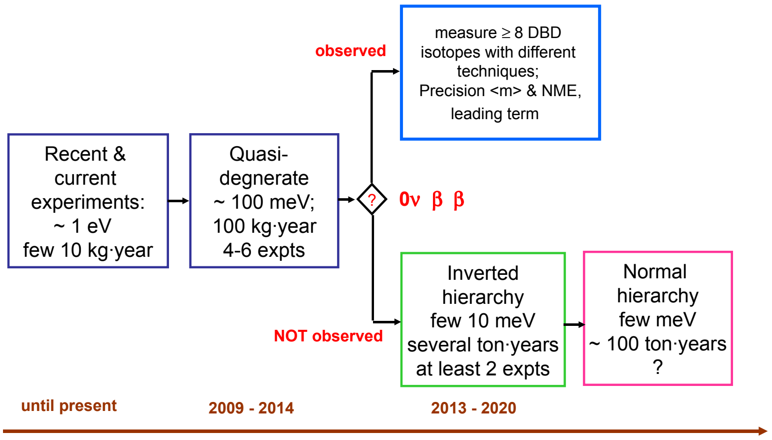

Figure 5. Time line and branching point for future double beta decay searches.

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