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# Nuclear Double Beta Decay and Fundamental Particle Physics

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## Introduction

Nuclear double beta decay, an extremely rare radioactive decay process, is – in one of its variants – one of the most exciting means of research into particle physics beyond the standard model. The large progress in sensitivity of experiments searching for neutrinoless double beta decay in the last two decades – based largely on the use of large amounts of enriched source material in 'active source experiments' – has lead to the observation of a first indication for the occurrence of this process in nature (on a 6.4 sigma level), with the largest half-life ever observed for a nuclear decay process ($2.2 \times 10^{25}$y). The fundamental consequences for particle physics – violation of lepton number, Majorana nature of the neutrino and others – present a challenge for future experiments.

## Double Beta Decay

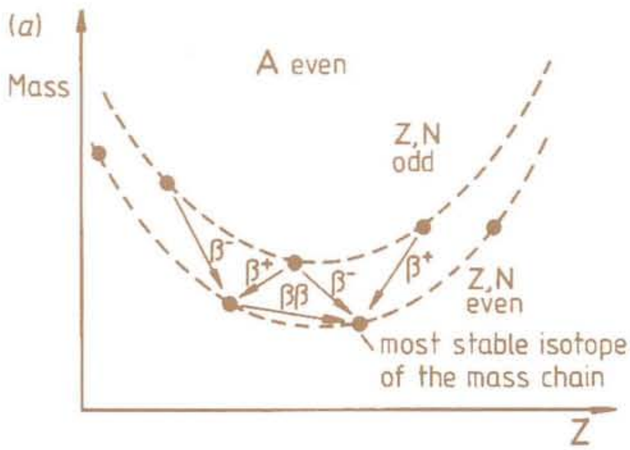
In the Nuclide Chart a special and intriguing role for the research into fundamental particle physics, astrophysics and cosmology is offered by neutron-rich nuclei more or less far from the stability line. In the 5. Edition in 1981 the editors of the Nuclide Chart were pioneering in including the first microscopic calculations of beta decay half-lives of nuclei far from stability which later were published in Nuclear Data Tables [1], and which lead to new insights into element synthesis by the astrophysical r-process, the age of the universe and cosmology (the cosmological constant) [2, 3].
There are about 35 neutron-rich nuclei, partly shown still as *stable* on the Nuclide Chart, which can undergo the so-called nuclear double beta decay – a second-order weak decay mode [3, 4].
The weak interaction is the most universal interaction after gravitation and operates on at least all fermions. It is the *only* interaction, which can alter the charge of the fermions (the most famous example is beta decay) and their flavours. From a perturbation theory point of view nuclear beta decay is understood as first order effect of the classical theory. In the Glashow-Weinberg-Salam (GWS) theory, in which the point-like current-current interaction is replaced by a boson exchange interaction nuclear beta decay is a second order effect. The very heavy bosons W± and Z are responsible for the extremely short range of the weak interaction. Double beta decay is a second order effect of the classical theory (and fourth order in the GWS theory). In the expression for the ββ decay rate the weak coupling constant (Fermi constant) which is of the order $G_\beta = 1.008 \cdot 10^{-5} \times m_p^{-2}$ enters in the fourth power and leads to extremely small half-lives. Double beta decay can become observable for nuclei for which no other decay process (in particular β decay) is possible. This is the case for several even-even nuclei (even number of protons and of neutrons) which because of the pairing energy have lower energy ground states than their odd-odd neighbours (odd number of protons and of neutrons). They may be converted into a more stable isotope only under double beta decay (see Fig. 1). This process may be understood as simultaneous β decay of two neutrons (for $\beta^-\beta^-$ decay) or of two protons (for $\beta^+\beta^+$ decay).
There are essentially two modes of double beta decay, the neutrino-accompanied ($2\nu\beta\beta$) mode, which is allowed in the Standard Model of Particle Physics and has been observed by geochemical experiments already since 1966, and by direct detection first in 1987 [11], and the neutrinoless mode ($0\nu\beta\beta$), which is *not* allowed in the Standard Model. In $2\nu\beta^-\beta^-$ decay (see Fig. 2) two electrons are emitted together with two electron-antineutrinos $\bar{\nu}_e$ (there are three types of neutrinos known, $\nu_e, \nu_\mu, \nu_\tau$), so that lepton number L is conserved:

$$\begin{array}{llllll} {}^Z_AX \rightarrow {}^{Z+2}_{\ \ A}X + 2e^- + 2\bar{\nu}_e & & & & & \\ L: 0 \quad 0 \quad +2 \quad -2 & \Rightarrow & \Delta L = 0 & & & (1) \end{array}$$



Much more interesting than $2\nu\beta\beta$ decay, which has been observed meanwhile for about ten nuclides, with half-lives of the order of $10^{19} - 10^{24}$ years, is the so-called neutrinoless double beta decay ($0\nu\beta\beta$), which may be viewed as an exchange of a neutrino between the two decaying nucleons (see Fig. 2):

$$\begin{array}{llll} {}^Z_AX \rightarrow {}^{Z+2}_{\ \ A}X + 2e^- & & & \\ L: 0 \quad 0 \quad +2 & \Rightarrow & \Delta L = 2 & (2) \end{array}$$



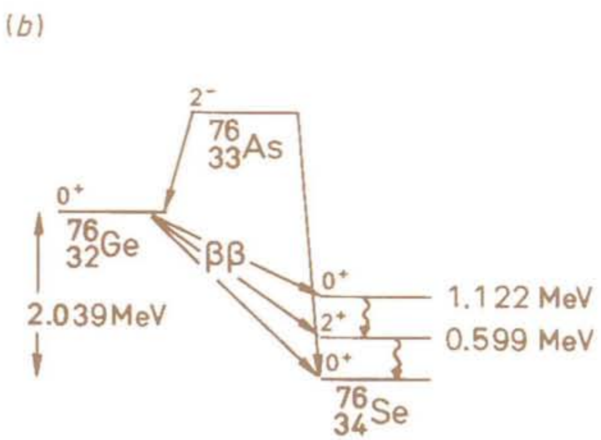




Fig. 1: a) Energetic situation of potential double beta emitters. Because of the pairing energy, nuclei with an even number of protons and an even number of neutrons are energetically depressed in comparison with neighbouring nuclei. Thus many nuclei are stable against single β decay, but may be converted into a more stable isotope under double beta decay. b) Schematic diagram of double beta decay of $^{76}Ge$.

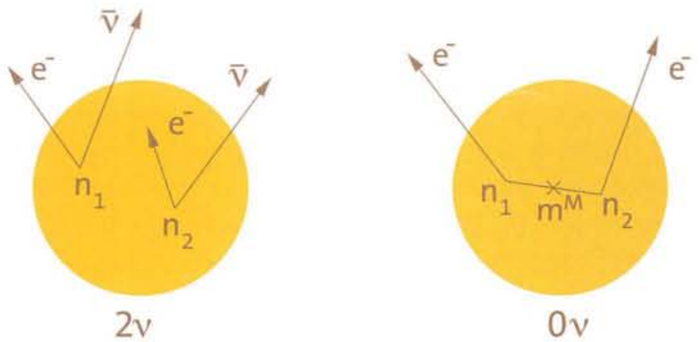



Fig. 2: The two main types of nuclear double beta decay: Two neutrons in a nucleus decay simultaneously under emission of two electrons and two antineutrinos – $2\nu\beta\beta$ decay – (left), or under emission of two electrons under exchange of a Majorana neutrino with non-vanishing mass $m^M$ between the decaying nucleons – $0\nu\beta\beta$ decay (right). The $2\nu$ and $0\nu\beta\beta$ processes have been first discussed by M. Goeppert-Mayer in 1935 and W. H. Furry in 1939, respectively.

In this case the (total) lepton number $L$ is *not* conserved. Total lepton number ($L$) is defined as the sum of the family lepton numbers $L_e, L_\mu, L_\tau$ ($L = L_e + L_\mu + L_\tau$). Non-conservation of family lepton number (but *not* of $L$) has been observed by so-called neutrino oscillations. $L$ was found in all experiments up to now, as also the baryon number, to be a conserved quantity in particle physics. The process of neutrinoless double beta decay is only possible if neutrino and antineutrino are identical i.e. the neutrino is a Majorana particle, (all other fermions known today are Dirac particles, where each particle has its defined antiparticle), *and* if either the neutrino has a non-vanishing mass, or there exists a right-handed weak interaction. In Grand Unified Theories (GUTs) the latter two conditions are not independent [18]. A right-handed component here is only effective in simultaneous association with a Majorana mass. If we go beyond the Standard Model, there are further mechanisms for $0\nu\beta\beta$ decay, such as Higgs boson exchange, exchange of a SUSY particle (gluino, photino, ...), etc.



The process (2) yields further broad access to many topics of particle physics beyond the standard model at the TeV range, on which new physics is expected to manifest itself. It can provide an absolute scale of the neutrino mass, and yields sharp restrictions for SUSY models, leptoquarks, compositeness, left-right symmetric models, test of special relativity and equivalence principle in the neutrino sector and others. For details, we refer to [6, 7].

The history of $\beta\beta$ decay using the nucleus as a complicated laboratory for a wide range of particle physics started about 70 years ago. This history is connected with fundamental discoveries of particle physics, such as parity non-conservation and of gauge theories, and double beta research has become one of the most important fields of non-accelerator particle physics. Concerning neutrino physics, without $0\nu\beta\beta$ decay there is no way to decide the nature of the neutrino (Dirac or Majorana particle), and of the structure of the $\nu$ mass matrix, since neutrino oscillation experiments measure only differences of neutrino mass eigenstates. Only investigation of neutrino oscillations and double beta decay together can lead to an absolute mass scale.

## Historical Development and Status of Search for Double Beta Decay – and the Neutrino Mass

The long and close association between the phenomenon of nuclear double beta decay, the violation of lepton number conservation and the nature and mass of the neutrino began shortly after the "discovery" of the neutrino by W. Pauli in 1930. The motivation of M. Goeppert-Mayer, however, when performing the first calculations of the half-life of $\beta\beta$ decay (in 1935) was not the nature of the neutrino, nor conservation of leptons, but the stability of even-even nuclei over geological times.

In 1939 W. H. Furry showed that the "symmetrical" theory of neutrino and antineutrino by E. Majorana (1937) could give rise to the process of neutrinoless double beta decay.

The first experiments on double beta decay were undertaken, before the existence of neutrinos was proved directly by Cowan and Reines (in 1955). While most of the very first experiments in the period 1948 – 1952 were looking for the decay electrons, a remarkable exception was the experiment performed by M. G. Inghram and J. H. Reynolds (1949, 1950). They looked for the daughter nucleus and exploited the fact, that measurable amounts of the daughter might accumulate over geological times in ores, which are rich in the corresponding parent nucleus. They analyzed a tellurium ore from Boliden, Sweden, which was about 1.5 billion years old, and reported evidence for the transition $^{130}Te \rightarrow {}^{130}Xe$ with a half-life of $1.4 \times 10^{21}$ years, which they attributed to $2\nu\beta\beta$ decay of $^{130}Te$. Another early approach was to look for radioactive daughter nuclei which in principle are detectable in much smaller quantities than stable rare gases. The experiment of Inghram and Reynolds was the forerunner of a series of geochemical experiments which definitely proved the occurrence of $2\nu\beta\beta$ decay, and confirmed their value within a factor of about 2. The first observation in "direct" experiments (not geochemical and radiochemical) was claimed in 1987, for $^{82}Se$. The first "active source experiment" (in which the detector material is at the same time the $\beta\beta$ emitter) was the one by E. der Mateosian and M. Goldhaber using $CaFe_2$, in 1966.

A particularly favourable case is presented by the $\beta\beta$ candidate $^{76}Ge$. This germanium isotope occurs with an abundance of 7.8 %

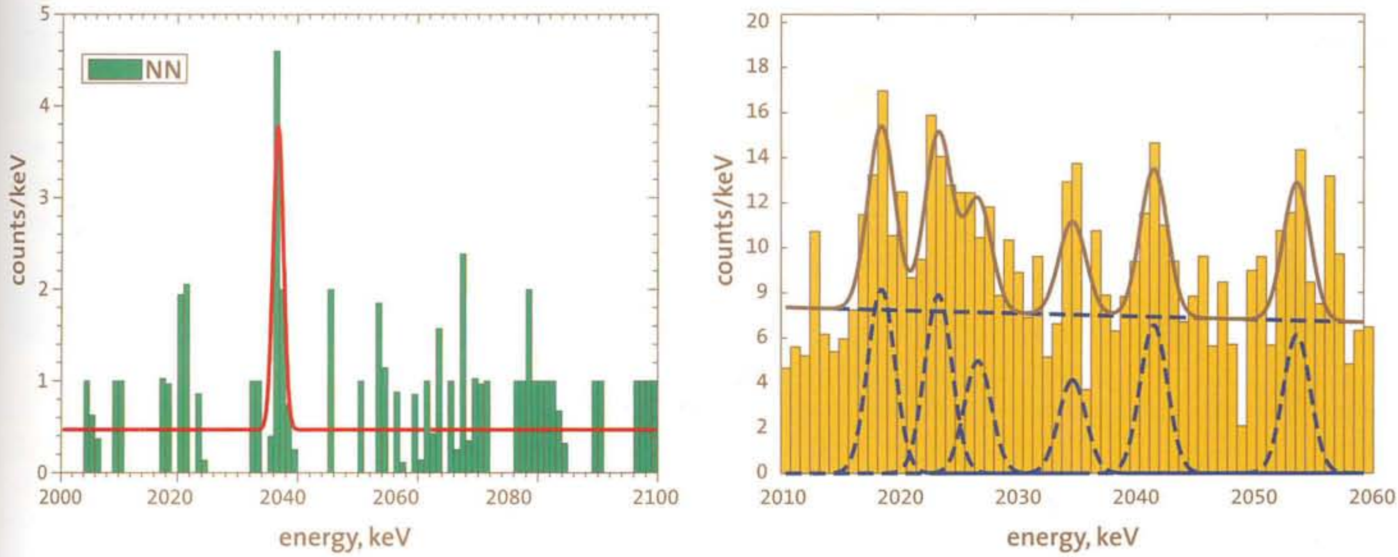



Fig. 3: The pulse shape selected spectrum in the range 2000 – 2100 keV taken with detectors 2, 3, 4, 5 (51.39 kg y) (left) and the corresponding full spectrum of all five detectors in the range 2010 – 2060 keV (56.66 kg y) (right), in the period 1995 – 2003 [9]. The $Q_{\beta\beta}$ value of $\beta\beta$ decay of $^{76}$Ge is known to be 2039.006 ± 0.050 keV.



in natural germanium, from which large high resolution detectors can be manufactured. Thus Ge can be used simultaneously as source and detector allowing for large source strength without spoiling the high energy resolution of such detectors. The most sensitive experiment using detectors from natural Ge was, over many years, the one by D. Caldwell in California, until in the early nineties the first Ge experiments using Ge enriched in the isotope $^{76}$Ge (to 86 %) were started. The use of enriched Ge drastically increased the sensitivity, and started a new era of $\beta\beta$ experiments. The largest experiment of this type (with 11 kg of enriched detectors) and the most sensitive experiment since 1993 until now is the Heidelberg-Moscow experiment [5], which was operated in the Gran Sasso underground laboratory from 1990 to 2003.

The result from the Heidelberg-Moscow experiment [9, 8] is shown in Figure 3. The background around $Q_{\beta\beta}$ is around $5\times10^{-3}$ counts/kg y keV, i.e. close to the level which had been planned in the GENIUS project [12]. The signal at $Q_{\beta\beta}$, where a $0\nu\beta\beta$ signal should occur, has a confidence level of $6.4\sigma$ (7.05 ± 1.11 events).

This is the first and up to now only indication for the occurrence of this process. Future experiments with adequate sensitivity have to be awaited to independently check this result. The intensity of the observed signal [9] corresponds to a half-life for $0\nu\beta\beta$ decay of $T_{1/2}^{0\nu\beta\beta} = (2.23^{+0.44}_{-0.31} \times 10^{25})$ y. From the half-life one can derive information on the effective neutrino mass $\langle m \rangle$ and the right-handed weak current parameters $\langle\eta\rangle$, $\langle\lambda\rangle$. Under the assumption that only one of the three terms (the effective mass term and the two right-handed weak current terms) contributes to the decay process, and ignoring potential other processes connected with SUSY theories, leptoquarks, compositeness, etc. [6], we find $\langle m \rangle = (0.32^{+0.03}_{-0.03})$ eV, or $\langle\eta\rangle = (3.05^{+0.26}_{-0.25}) \times 10^{-9}$, or $\langle\lambda\rangle = (6.92^{+0.58}_{-0.56}) \times 10^{-7}$. These are the upper limits for these quantities. When 'calibrating' the corresponding matrix element from the measured rate of $2\nu\beta\beta$ decay of $^{76}$Ge [9] the effective neutrino mass becomes lower, down to 0.22 eV.

The effective electron neutrino mass is $\langle m_\nu \rangle = | \Sigma (U^*_{ei})^2 m_i |$, where $U^*_{ei} = \langle \nu_e | \nu_i \rangle = \langle \nu_i | \nu_e \rangle^*$, and $|\nu_e\rangle = \Sigma_i \, U_{ei} |\nu_i\rangle$. From the observation of solar, atmospheric and accelerator neutrinos, so-called neutrino oscillations have been observed, i.e. transitions from one neutrino flavour into another, e.g. $\nu_e \rightarrow \nu_\mu$. These experiments allow to determine the difference of the $\nu$ mass eigenstates (which are found to be of the order of 0.008 and 0.05 eV) [16, 17], and their flavour composition. The absolute neutrino masses cannot be determined by neutrino oscillation experiments. From neutrino oscillation experiments one can determine the mixing parameters and thus the effective mass $\langle m \rangle$ to be expected in $0\nu\beta\beta$ experiments for different $\nu$ mass scenarios (different $\nu$ mass models). Figure 4 shows these expectations together with the value of $\langle m \rangle$ determined from the Heidelberg-Moscow experiment (under the assumption of dominating mass mechanism). It can be seen that in a scenario of three neutrino flavours only the solution of degenerate (i.e. essentially identical, except for the small differences determined by neutrino oscillation experiments) masses remains. All other mass models (hierarchical, inverse hierarchy, partially degenerate, ...) are excluded. The common mass eigenvalue corresponding to this effective mass can be determined with recent mixing angles from solar neutrinos to be 0.2 – 0.48 eV [6, 19].

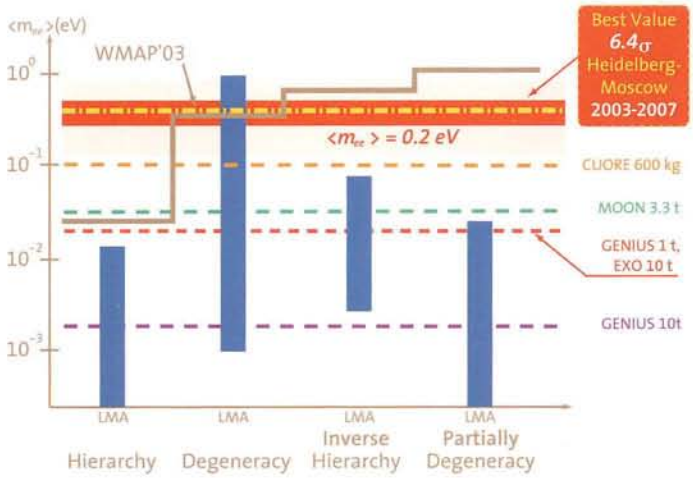



Fig. 4: Summary of expected values for the effective neutrino mass $\langle m_{ee} \rangle$ in different neutrino mass schemes and the result of the Heidelberg-Moscow experiment. The bars denote allowed ranges of $\langle m \rangle$ in different neutrino mass scenarios, still allowed by neutrino oscillation experiments [9, 10]. All models except the degenerate one are excluded by the $0\nu\beta\beta$ decay result. Also shown is the exclusion line from WMAP, plotted for $\Sigma m_\nu < 1.0$ eV, (which is according to [14], too strict). WMAP does not rule out any of the neutrino mass schemes. Further shown are for history the expected sensitivities expected earlier for the planned double beta experiments CUORE, MOON, EXO and the 1 ton and 10 ton project of GENIUS [6, 12].



The analysis of the cosmological experiments SDSS (Sloan Digital Sky Survey) and WMAP (Wilkinson Microwave Anisotropy Probe) together [14] yields an upper limit for the sum of the neutrino masses of $\Sigma m_\nu < 1.7$ eV (95 % c. l.). This would correspond to $\leq 12$ % of dark matter in the universe. The SDSS result means that the individual neutrino mass should be smaller than ~ 0.6 eV, which is consistent with the above value from double beta decay. Figure 4 shows as example the limits set by the cosmic microwave experiment WMAP (assuming $\Sigma m_i = 1.0$ eV).

## Summary and Outlook

Nuclear double beta decay has developed in the last decades to one of the most exciting means of the research into physics beyond the standard model. For the first time, an indication has been found that the process of $0\nu\beta\beta$ decay is occurring in nature. Because of its fundamental consequences for particle physics, this is a huge challenge for future experiments. For a better understanding of the various mechanisms contributing to the $0\nu\beta\beta$ amplitude, we will have to go to completely different types of experiments, than presently persued [6, 9, 13].

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