Double Beta Decay and Neutrino Mass. The Heidelberg-Moscow experiment

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Abstract:

The status of research in double beta decay is reviewed. Double beta decay experiments yield at present the sharpest limits on the electron neutrino mass, right-handed coupling constants, the neutrino-Majoron coupling constant, and the best laboratory limit on the half-life of electron decay. A new era of second generation $\beta\beta$-experiments just started and will be dominated by use of enriched detectors. One of the most advanced projects is the HEIDELBERG-MOSCOW experiment having at its disposal 16.9 kg of enriched ^{76}Ge.

Concerning the calculations of nuclear matrix elements for $\beta\beta$ decay, a major step beyond the frequently used QRPA model has been made by introducing the Operator Expansion Method.

1 Introduction

The neutrino is one of the best examples for the merging of the different disciplines of micro- and macrophysics (Fig.1). The neutrino plays, by its nature (Majorana or Dirac particle) and its mass, a key role for the structure of modern particle physics theories (GUTs, SUSYs, SUGRAs, ...). At the same time it is candidate for non-baryonic dark matter in the universe, neutrinos are a unique way to probe the interior of collapsing stars, etc.

In the search for the neutrino mass we can differentiate between different approaches (Fig.2), which may be classified as terrestrial and extra-terrestrial, among the latter the most spectacular being the investigation of solar neutrinos [ham87, sin87, ans92] and neutrinos from supernovae [mey87]. In principle also the up to now unobserved cosmic neutrino background radiation contains a mass information (see, e. g. [mül87]). Since the solar neutrino experiments measure the difference of the (squared) mass eigenvalues of different neutrino flavors $\Delta m^2 = | m_1^2 - m_2^2 |$, they primarily yield information on the heavier neutrino flavors and thus are *complementary* to those non-accelerator experiments like β and $\beta\beta$ decay measuring directly

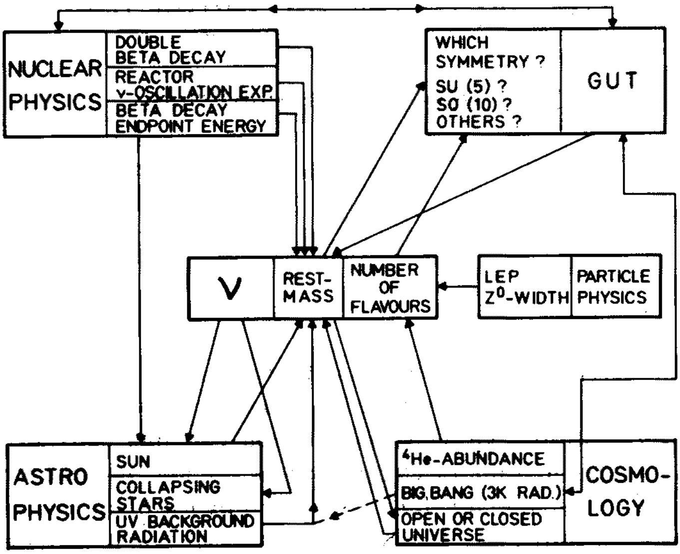


Figure 1: The neutrino and its role in micro- and macrophysics

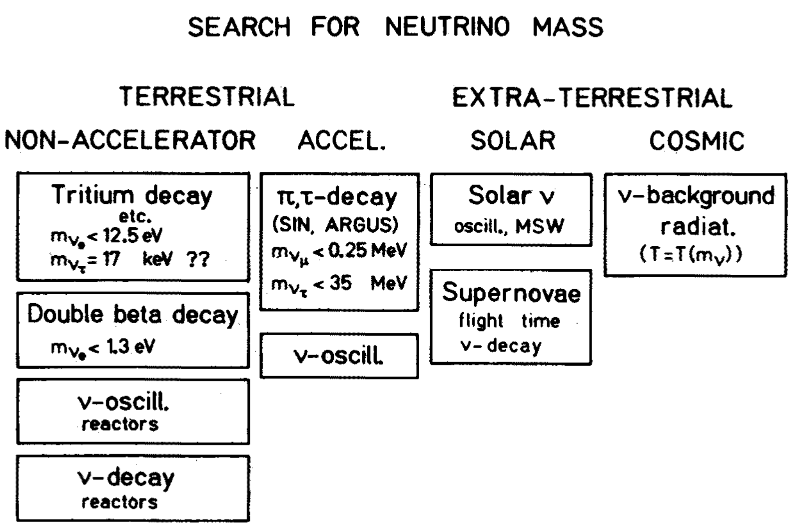


Figure 2: Classification of experiments investigating the neutrino mass

the electron neutrino mass (or more precisely an effective neutrino mass dominated by the mass eigenstate of the electron neutrino).

The sharpest limits on the electron neutrino come at present from non-accelerator experiments: tritium decay and double beta decay. Both experiments again are complementary: while the effect of a neutrino mass in the β decay spectrum of tritium is independent of the nature of the neutrino (Dirac or Majorana particle, see Fig.3), double beta decay can measure only an effective Majorana mass of the neutrino . So only study of both processes together gives the required information on the Dirac and Majorana mass terms in the neutrino mass matrix. Double beta decay can also probe in a very sensitive way the hypothesis of a 17 keV neutrino, if this is a Majorana particle, by its influence on the effective mass observed in $\beta\beta$ decay.

The outline of this paper is as follows. In sections 2,3 we mention some expectations for neutrino masses from particle physics theories and cosmology. For more details we refer to the papers by Khlopov [khlo92] and by Valle [val92]. In section 4 we describe the present status of research in $\beta\beta$ decay, for which a new era of second generation experiments using detectors from enriched material just started. We critically discuss the theory of nuclear structure necessary to deduce information on the neutrino mass from such experiments and then give a report of the experimental status and perspectives. We particularly also report the present status and first results of the Heidelberg-Moscow experiment.

2 Neutrino mass and particle physics theories - (GUTs, SUSYs)

The neutrino mass is one of the key quantities for the structure of grand unified theories (GUTs, SUSYs, SUGRAs) (see e. g. [gro90, kla88, moh91, val92]. Most grand unified theories except the simplest (minimal $SU(5)$) predict a non-vanishing neutrino mass in a natural way. E. g. already in the simplest left-right symmetry model, $SO(10)$, there exists a right-handed neutrino (the $SU(5)$ singlet in Fig.4), its Dirac mass being in lowest order of the order of the u quark mass. To obtain consistency with observation, the way of the see-saw mechanism [gel79, yan79] is to introduce an even larger right-handed Majorana mass term m_R^M in the neutrino mass matrix which is, simplified to the one flavor case

$$\left(\bar{\nu}_L \overline{(\nu_R)^C}\right) \begin{pmatrix} 0 & m_D \\ m_D & m_R^M \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix} \qquad \begin{matrix} m_R^M & \gg & m_D \\ m_D & \simeq & \text{MeV} \end{matrix} \tag{1}$$

This leads to the phenomenologically required light (Majorana) neutrino

$$\nu_1 = \nu_L - \frac{m_D}{m_R^M}\nu_R \qquad \text{with} \qquad m_1 \approx \frac{(m^D)^2}{m_R^M} < (\text{eV}) \tag{2}$$

and to a heavy (Majorana) neutrino with $m_2^M \simeq m_R^M$.

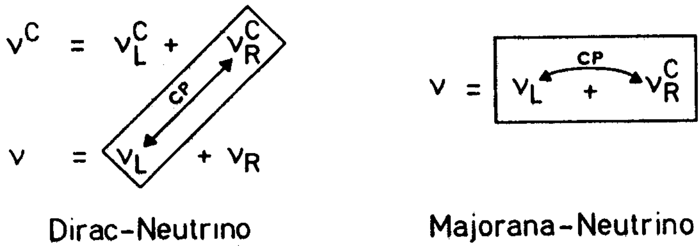


Figure 3: Possible assignment of the experimentally known (in boxes) neutrino states (of one family) in the theoretical description for Dirac and Majorana fields

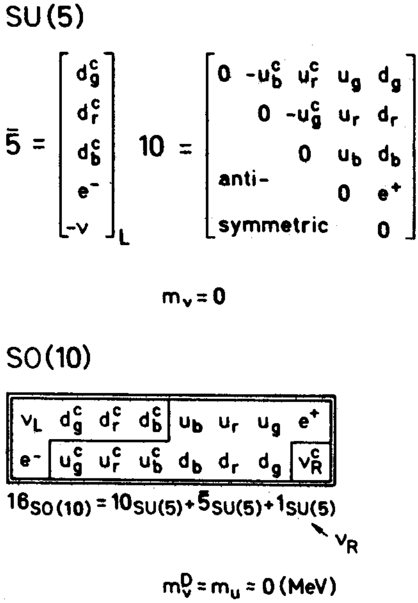


Figure 4: Multiplets of the fermions of the first generation in the $SU(5)$ and $SO(10)$ model

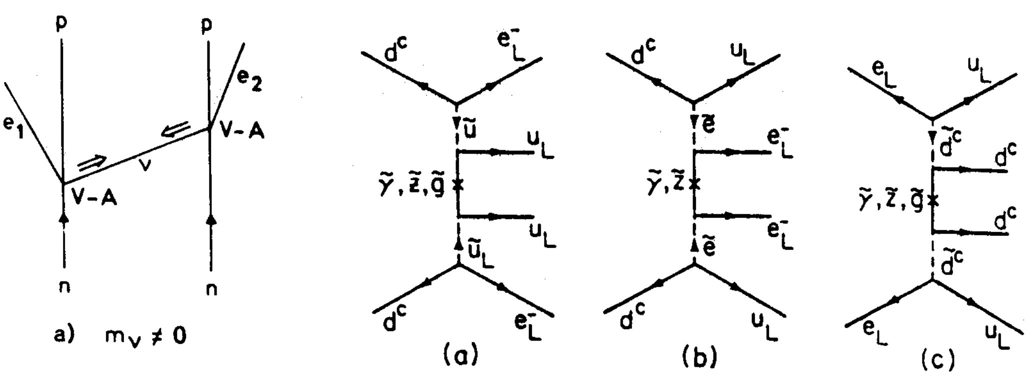


Figure 5: Transition modes for $\beta\beta_{0\nu}$ decay in GUT models (left) and in some supersymmetric extension of the standard model. In the latter the dominating amplitudes are gaugino (gluino, photino, zino) exchange (see [moh86b])

Introduction of m_R^M is, on the other hand, equivalent to $(B-L)$ nonconservation - and equivalent to the occurrence of neutrinoless double beta decay.

Since m_R^M is produced in GUTs when breaking left-right symmetry, its value and consequently the neutrino mass can range over a wide scale, depending on the energy scale at which left-right symmetry is broken [doi85]. This might happen in the range of the two examples

$$(a) \qquad SO(10) \overset{M > M_X}{\longrightarrow} SU(5) \overset{M_X}{\to} SU(3)_c \otimes SU(2)_L \otimes U(1) \qquad (3)$$

or

$$(b) \qquad SO(10) \to \underbrace{SU(4)_{EC}}_{\substack{\text{extension of strong}\\ \text{interaction (extended color)}\\ \text{with leptons as 4. color charge}}} \otimes \underbrace{SU(2)_L \otimes SU(2)_R}_{\substack{\text{right}-\text{handed}\\ \text{bosons } W_R^{\pm}}} \qquad (4)$$

between 10^{15} GeV (a) or 100 GeV (Pati-Salam model, (b)). This is the energy range probed by $\beta\beta_{0\nu}$ decay, which is reflected directly by the neutrino mass (see Table 1).

Consequently the predictive power of GUTs for the neutrino mass is extremely weak: $m_\nu \simeq 10^{-11} - \simeq 1$ eV (see Table 1), which on the other hand reflects the importance of experimental information for selecting the "right" GUT model. For predictions of other types of models see [moh86a, moh91, khlo92, val92]. Some of these models and also Table 1 show, that one should not be biased to look only for very small neutrino masses. Another question is the sensitivity of the various experiments, in particular those of double beta decay, to an assumed neutrino mass. In SUSY models, for example, such as a supersymmetric extension of the standard model, neutrino exchange could give only a small contribution to $\beta\beta_{0\nu}$ decay, and the latter could be dominantly induced by gaugino (gluino, photino and zino) exchange [moh86b, moh91] (see Fig.5).

This is a point deserving attention - particularly in the light of the recent extrapolations of LEP results on electroweak and strong coupling constants [ama91], which indicate that in the frame of the minimal standard model only a supersymmetric version (with two Higgs doublets) is compatible with a simple GUT unification scale (of $10^{16.0\pm0.3}$ GeV). It can be shown, however [moh91], that while observation of $0\nu\beta\beta$ decay thus may not be directly translated in a model-independent way to a *value* for the neutrino mass, it certainly can be used to infer the *existence* of a non-vanishing Majorana neutrino mass regardless of whatever mechanism causes $0\nu\beta\beta$ decay to occur.

It is obvious that also in the case that the neutrino mass would be so small that it is not in the range which can be probed by $\beta\beta_{0\nu}$ decay, such experiments would remain a sensitive probe of physics beyond the standard model.

Table 1: Models of neutrino mass, along with their most natural scales for the light neutrino masses (from [lan88]; it may be noted that in most cases $m_{\nu_e} = \langle m_{\nu_e} \rangle$)

Model	m_{ν_e}	$\langle m_{\nu_e} \rangle$	m_{ν_μ}	m_{ν_τ}
Dirac	1-10 MeV	0	100 MeV-1 GeV	1-100 GeV
pure Majorana (Higgs triplet)	arbitrary	m_{ν_e}	arbitrary	arbitrary
GUT seesaw ($M \approx 10^{14}$ GeV)	10^{-11} eV	m_{ν_e}	10^{-6}eV	10^{-3} eV
intermediate seesaw ($M \approx 10^{9}$ MeV)	10^{-7} eV	m_{ν_e}	10^{-2} eV	10 eV
$SU_{2L} \otimes SU_{2R} \otimes U_1$ seesaw ($M \approx$1 TeV)	10^{-1} eV	m_{ν_e}	10 keV	1 MeV
light seesaw ($M \ll$1 GeV)	1-10 MeV	$\ll m_{\nu_e}$		
charged Higgs	<1 eV	$\ll m_{\nu_e}$		

It has to be kept in mind also that if the electron neutrino is a mixed state (m matrix is not diagonal in the flavor space):

$$| \nu_e \rangle = \sum_i U_{ei} \mid \nu_i \rangle \tag{5}$$

then the measured quantity in double beta decay is an effective mass

$$\langle m_\nu \rangle = \sum_i m_i U_{ei}^2 \tag{6}$$

which for appropiate CP phases of the mixing coefficients U_{ei} could be smaller than m_i for all i [wol81]. Neutrino oscillation experiments yield some restrictions of this possibility (see [gro86b, gro90]). Table 1 illustrates that in general not too pathological models seem to yield $m_{\nu_e} = \langle m_{\nu_e} \rangle$.

3 Cosmology and neutrino mass

3.1 Neutrino mass and dark matter

An upper limit for the neutrino mass can be obtained from an estimate of the amount of non-baryonic dark matter in the universe in two ways.

3.1.1 Cosmological models

The expansion of a homogeneous and isotropic universe with a Robertson-Walker metric can be described by the radius of curvature $R(t)$ of the three-dimensional space manifold at time t after the big bang:

$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{(R(t))^2} + \frac{1}{3}\Lambda c^2 \tag{7}$$

$$\frac{\ddot{R}(t)}{R(t)} = -\frac{4\pi G}{3}\left[\rho(t) + \frac{3p(t)^2}{c^2}\right] + \frac{1}{3}c^2 \tag{8}$$

Here $\rho(t)$ is the mean density of matter, $p(t)$ the radiation pressure in the universe; k is the metric parameter describing sherical, Euclidean and hyperbolic spaces for $k=$ +1, 0, -1, respectively, and Λ is the cosmological constant which cannot be fixed by general relativity. In most cosmological models Λ was assumed to be zero (mainly from "esthetical" reasons). However, in the context of quantum field theory Λ can be interpreted [zel68] as energy density of the vacuum ϵ_V,

$$\Lambda = \frac{8\pi G}{c^4}\epsilon_V \tag{9}$$

and there is no reason for the latter to be zero. Very high vacuum energies (or equivalent vacuum matter densities $\rho_V = \epsilon_V/c^2$) are required in order for inflation [gut81, lin82] to develop at some very early time t ($t \approx 10^{-35}$ s) after the big bang (one must have $\rho_V \geq \rho(t)$ at this time). Such large vacuum energies may result from the Higgs fields introduced in gauge theories. From observation the value at present is [abb88] $\Lambda \leq 3 \cdot 10^{-56}$ cm^{-2}.

To obtain a solution for $R(t)$ three boundary conditions are required. One of them can be the age of the universe, the two others the Hubble constant $H_0{=}\dot{R}/R$ today and the matter density ρ_0 of the universe today. The latter two quantities are fixed by observation still only with relatively wide limits (H_0=40-100 km/Mpc·s, $\rho_0 \geq \rho_B = (0.5^{+0.7}_{-0.3}) \cdot 10^{-30}$ g·cm^{-3}; ρ_B here denotes the baryonic matter density in the universe (including *baryonic* dark matter) which can be determined from primordial nucleosynthesis (see, e. g., [blo84]).

Figures 6 and 7 show the relation between age of the universe and present matter

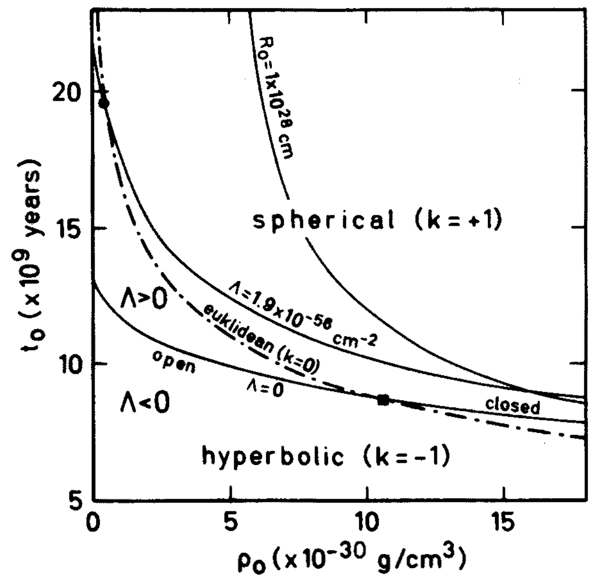


Figure 6: Relation between the age of universe t_0 and present cosmic matter density ρ_0 for various cosmological model types, with cosmological constant Λ and metric parameter k as parameters (H_0 is fixed to 75 km/Mpc·s). In Friedmann-Einstein models (Λ=0) t_0 cannot exceed 13·10^9 y. Moreover this limiting value would only be obtained in strongly hyperbolic models without dark matter, Euclidean metric would restrict t_0 further to 8.7 Gy. Larger values for t_0 can be obtained in Euclidean models if $\Lambda > 0$ (from [kla86])

density ρ_0 for various cosmological model types with Λ and k as parameters (H_0 is fixed in these figures to an average value of 75 km/Mpc·s); q_0 in Fig. 7 denotes the deceleration parameter, $q_0 = -[\ddot{R}(t)R(t)/\dot{R}(t)^2]_{t=t_0}$, which is fixed by observation to -1.27< q_0 <2.

With Euclidean metric (favoured by inflation according to many authors, but questioned as necessary consequence of inflation by [mad88, hoe90]), and Λ=0, the age would be only t_0=8.7 Gy (for H_0=75 km/Mpc·s). The simultaneous requirements Λ=0 and Euclidean metric require further a large amount of non-baryonic dark matter ρ_D in the universe: $\rho_0 = \rho_B + \rho_D \gg \rho_B$. If one allows, however, for $\Lambda > 0$ ($\rho_V \neq 0$) (Friedmann-Lemaître models), the Euclidean models can give t_0 to the right range according to globular clusters and cosmochronometers and at the same time, the non-baryonic matter ρ_D required would be largely reduced. A positive vacuum energy density to a large amount "replaces" the dark matter needed to obtain Euclidean metric *and* Λ=0.

We find [kla86] that for ages $t_0 > 13 \cdot 10^9$ y in the case of Euclidean metric solutions with $\Lambda = 0$ would be excluded for H_0 ≥50 km/Mpc·s. For a Hubble constant H_0 ≥43 km/Mpc·s the value of Λ would become positive for $t_0 >$ 15.2

Gy. For an Euclidean universe with $t_0 \geq 17$ Gy we obtain, assuming H_0=(50-100) km/Mpc·s, a value of $\Lambda = (0.47 - 1.9) \cdot 10^{-56}$ cm^{-2} or, correspondingly, $\rho_D = (2.5 - 10) \cdot 10^{-30}$ g·cm^{-3}.

From the amount of non-baryonic dark matter we can finally deduce an upper limit for the neutrino mass. Adopting an Euclidean metric and an age of 15 Gy, attributing of the non-baryonic dark matter completely to neutrinos (of course, there are many other candidates for dark matter, see e. g. [sch86, gro90]) whose cosmic density is known to be ~330 cm^{-3}, we can read [kla86] an average neutrino mass (three flavors)

$$\bar{m}_\nu = \frac{1}{3}\sum_{i=1}^{3} m_\nu^{(i)} \tag{10}$$

from the upper scale given in Fig. 7 to be $\bar{m}_\nu$=2 eV for H_0 =75 km/Mpc·s. Correspondingly, we obtain $\bar{m}_\nu$=4 eV for H_0 =50 km/ Mpc·s. If no assumption on the metric is made and only the restriction $H_0 \geq 50$ km/Mpc·s is used, the less stringent limit $\bar{m}_\nu$=18 eV is obtained. Would the masses of ν_e, ν_μ, ν_τ be related as those of the e, μ and τ leptons (see, e. g. [moh88]) a value of $m_{\nu_e} \leq 10^{-3}$ eV would be obtained.

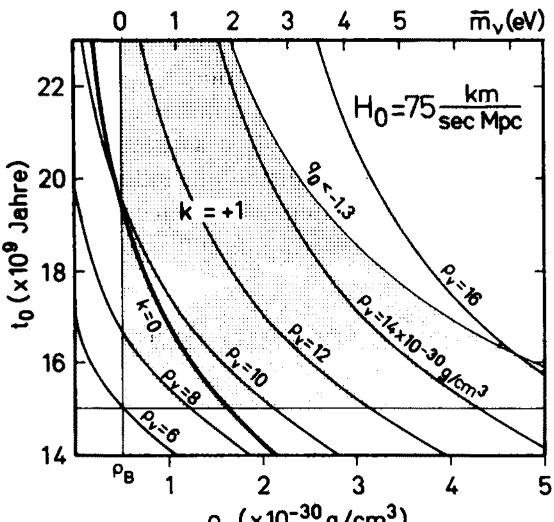


Figure 7: The relation between t_0 and ρ_0 as in Fig. 6, however, the parameter range of interest shown in more detail. The hatched area corresponds to boundary conditions $\rho_0 \geq \rho_B$, $q_0 < -1.3$ and t_0 =15 Gy. In this area only models with $\rho_V > 0$ are allowed. For Euclidean metric (k=0) this holds also for H_0=50 km/Mpc·s down to ages t_0 >13 Gy. An upper limit of the neutrino mass can be read from the upper scale, corresponding to attributing the non-baryonic dark matter $\rho_D = \rho_0 - \rho_B$ to neutrinos (from [kla86])

3.1.2 Large scale structure of the universe and galaxy formation

The large-scale distribution of the galaxies and development of large-scale structure of the universe have recently been reconsidered [tay92, dav92] in the light of the new COBE-results on the microwave background fluctuations [wri92, smo92], and the QDOT IRAS redshift survey. They come, by a study of an array of structure formation models, to the conclusion that there is only one satisfactory model for a universe with $\Omega = 1$, namely a model with about 70% in the form of cold dark matter and 30% of hot dark matter, the latter in form of two massless neutrinos and one stable neutrino with mass of 7.5 ± 2 eV (1σ). (The case of three equally massive neutrinos was not considered; it was argumented because of the strong limits on the electron neutrino mass). In the previous subsection a very similar result was obtained assuming instead of the cold dark matter part a non-vanishing energy density of the vacuum. Such a mixed dark matter (MDM) model seems to resolve a long-standing problem of large-scale structure, namely the disparate estimates of Ω on small and large scales.

3.2 Neutrino mass and very early universe

The neutrino mass is not only connected to the dark matter problem of cosmology. There is also a connection to the development in the very early universe. It has been pointed out [fuk90, yan92] that the baryon number asymmetry in the universe is erased by the sphaleron effect just below the electroweak phase transition irrespective to the primordial baryon- and lepton-number asymmetry, if there exist sizeable Majorana-type interactions which are often assumed to explain small Majorana masses for neutrinos. The survival condition of the baryon asymmetry of the Universe gives a constraint on such interactions and hence on the neutrino masses: $m_\nu < 50 keV$ for the heaviest Majorana neutrino [fuk90], or $m_{\nu_\tau} < 15 eV$ [yan92].

4 Double beta decay, neutrino mass and Majoron emission

There are several decay modes discussed in $\beta\beta$ decay, the main ones being two neutrino (2ν) and neutrinoless (0ν) decay (Fig.8)

$$ {}^A_Z X \rightarrow {}^A_{Z+2}X + 2e^- + 2\bar{\nu}_e \quad (11)$$

$$ {}^A_Z X \rightarrow {}^A_{Z+2}X + 2e^-. \quad (12)$$

In addition there could occur 0ν decay accompanied by emission of one or two majorons (Fig.8)

$$ {}^A_Z X \rightarrow {}^A_{Z+2}X + 2e^- + \chi \quad (13)$$

$$ {}^A_Z X \rightarrow {}^A_{Z+2}X + 2e^- + \chi + \chi. \quad (14)$$

Fig.9 shows the corresponding spectral shapes of the electron sum spectra. In SUSY models modes other then (12)-(14) might dominate $0\nu\beta\beta$-decay (see Fig.5).

The first process is a usual effect of second order in the classical weak interaction, the second requires as a prerequisite a non-vanishing Majorana neutrino mass or a right-handed weak interaction. In the framework of GUTs, or more general gauge

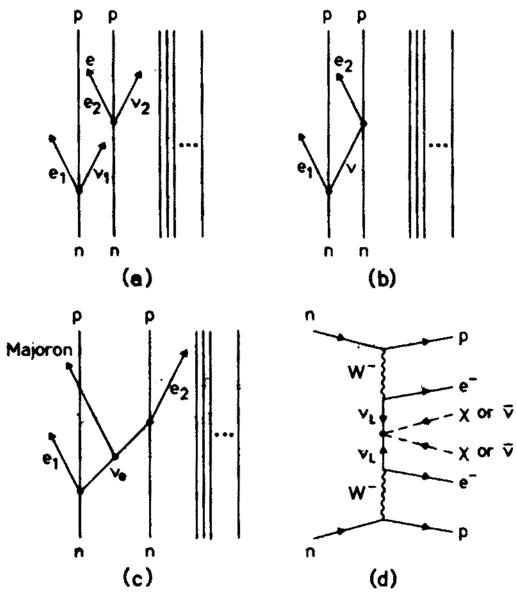


Figure 8: Graphs for $\beta\beta_{2\nu}$, $\beta\beta_{0\nu}$, $\beta\beta_{0\nu\chi}$ and $\beta\beta_{0\nu2\chi}$ decay

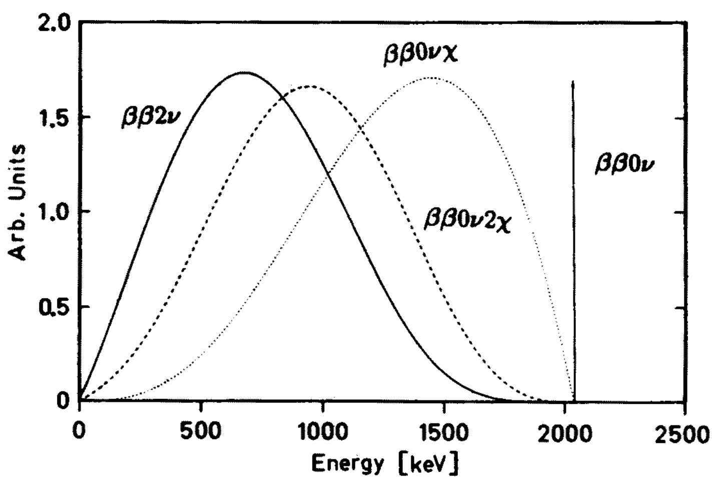


Figure 9: Shapes of the electron sum spectra in the cases of $\beta\beta_{2\nu}$, $\beta\beta_{0\nu}$, $\beta\beta_{0\nu,\chi}$ and $\beta\beta_{0\nu2\chi}$ decay (for the case of ^{76}Ge decay)

theories, both of these conditions cannot be seen independently, but in any case a non-vanishing mass is required [moh86a, ros88].

There are three possibilities to break B-L in theory [moh91], which is required to produce a Majorana mass: (1) explicit B-L breaking, i.e. the Lagrangian contains B-L violating expressions; (2),(3) spontaneous breaking of a local or global B-L symmetry. The existence of the massless Nambu-Goldstone boson called majoron χ is associated with the third possibility. From the different majoron models characterized by their weak isospin, connected with different possibilities to generate Majorana mass terms in extensions of the standard model two are ruled out by the recent LEP measurements [ste91]: the triplet majoron [gel81], which would contribute [geo81] an effect equivalent to two neutrino flavours to the Z^0 width, and the doublet majoron [moh88, moh91], which should contribute half a neutrino width. However the existence of singlet majorons [chi80] or a mixture of singlet- and doublet majorons is possible and might occur in $\beta\beta$ decay (see, e.g. [ber92, smi92]). Investigation of the doublet majoron, which would be associated with a double beta decay mode with emission of two majorons (Fig. 8), could allow to make conclusions on the Zino mass (see below). The model of singlet majorons has recently experienced large interest in connection with attempts to construct neutrino mass hierarchies involving a 17 keV neutrino [gla91, bab91, cho92]. It is therefore important to search for this decay mode.

4.1 Calculation of the required matrix elements

For $\beta\beta_{2\nu}$ decay the half life $T_{1/2}$ is given by [doi85, gro83, gro86b] (for a derivation see [gro90])

$$\begin{aligned}
[T^{2\nu}_{1/2}(0^+ \to 0^+)]^{-1} &= \frac{a^{2\nu}}{\ln 2} \int\limits_{m_e}^{T_0+m_e} F_0(Z,e_1)k_1 e_1\, de_1 \\
&\times \int\limits_{m_e}^{T_0+2m_e-e_1} F_0(Z,e_2)k_2 e_2\, de_2 \\
&\times \int\limits_{0}^{T_0+2m_e e_1-e_2} \nu_1^2\nu_2^2\, d\nu_1 \sum_{\alpha,\alpha'} A_{\alpha\alpha'} \qquad (15)
\end{aligned}$$

with $T_0 = e_1 + e_2 - 2m_e + \nu_1 + \nu_2$, $a^{2\nu} = \frac{G^4 g_A^4}{32\pi^7 m_e}$. The half life for $\beta\beta_{0\nu}$ decay is given by [doi85, mut88b]

$$\begin{aligned}
[T^{0\nu}_{1/2}(0^+_i \to 0^+_f)]^{-1} &= C_{mm}\frac{<m_\nu>^2}{m_e^2} + C_{\eta\eta} <\eta>^2 + C_{\lambda\lambda} <\lambda>^2 \qquad (16) \\
&+ C_{m\eta} <\eta> \frac{<m_\nu>}{m_e} + C_{m\lambda} <\lambda> \frac{<m_\nu>}{m_e} + C_{\eta\lambda} <\eta><\lambda>
\end{aligned}$$

or, when neglecting the effect of right-handed weak currents, by

$$[T^{0\nu}_{1/2}(0^+_i \to 0^+_f)]^{-1} = C_{mm}\frac{< m_\nu >^2}{m_e} = (M^{0\nu}_{GT} - M^{0\nu}_F)^2 G_1 \frac{< m_\nu >^2}{m_e} \qquad (17)$$

where G_1 denotes the phase space integral.

The half-life for $0\nu\chi$ decay is given by [doi88]

$$[T_{1/2}]^{-1} = (M^{0\nu}_{GT} - M^{0\nu}_F)^2 F^{0\nu\chi}(\langle g_{\nu\chi}\rangle)^2 \qquad (18)$$

Here the neutrino-majoron coupling constant $\langle g_{\nu\chi}\rangle$ is given by

$$\langle g_{\nu\chi}\rangle = \sum_{i,j} g_{\nu\chi} U_{ei} U_{ej} \qquad (19)$$

and $F^{0\nu\chi}$ denotes the phase space (for the latter see [doi88]).

The half life of the $0\nu\chi\chi$ decay is [moh88, moh91]

$$[T_{1/2}]^{-1} = (f_{\chi\chi} - m_e)^2 (M^{0\nu}_{GT} - M^{0\nu}_F)^2 F^{0\nu\chi\chi} \qquad (20)$$

The coupling constant $f_{\chi\chi}$ here is connected with the Zino mass according to

$$f_{\chi\chi} = \frac{g^2}{4M_Z cos\Theta_W} \qquad (21)$$

with the Weinberg angle Θ_W being assumed to be identical to that in the standard model in the supersymmetric domain.

The nuclear matrix elements $M^{0\nu}_{GT}, M^{0\nu}_F$ in eq. (18),(20) are the same as for the case of $0\nu\beta\beta$ decay (if exchange of heavy neutrinos is ignored).

Thus a reliable ν mass or right-handed coupling constant or neutrino-majoron coupling constant or other more exotic quantities can be extracted from a measured rate only if the nuclear matrix element $M^{0\nu} = (M^{0\nu}_{GT} - M^{0\nu}_F)$ can be reliably calculated.

After the major step of recognizing the importance of g. s. correlations for the calculation of 2ν and 0ν $\beta\beta$ matrix elements [gro85, gro86b, kla84], in recent years the main groups used the QRPA model [civ87, mut88a, mut88b, mut89, mut91, sta90b, vog86]. It was found that though in most cases the uncertainties of the model were tolerable in the case of $\beta\beta_{0\nu}$ decay (see Fig.10) this was not so for the 2ν decay (see Fig.12 and [mut88b, mut89]). For the latter essentially only reliable lower limits of the half-lives were predictable in this model.

The much larger sensitivity of calculated matrix elements for $\beta\beta_{2\nu}$ decay to ground state correlations of initial and final states than in $\beta\beta_{0\nu}$ decay, observed already by [gro86b, kla84], is meanwhile physically understood [mut89]. The 2ν decay mode (between two 0^+ states) can be described as successive Gamov-Teller transitions via virtual intermediate 1^+ states. In the case of $\beta\beta_{0\nu}$ decay - as a consequence of the neutrino potential $H(r)$ occurring in the matrix element $M^{0\nu}_{GT}$ -

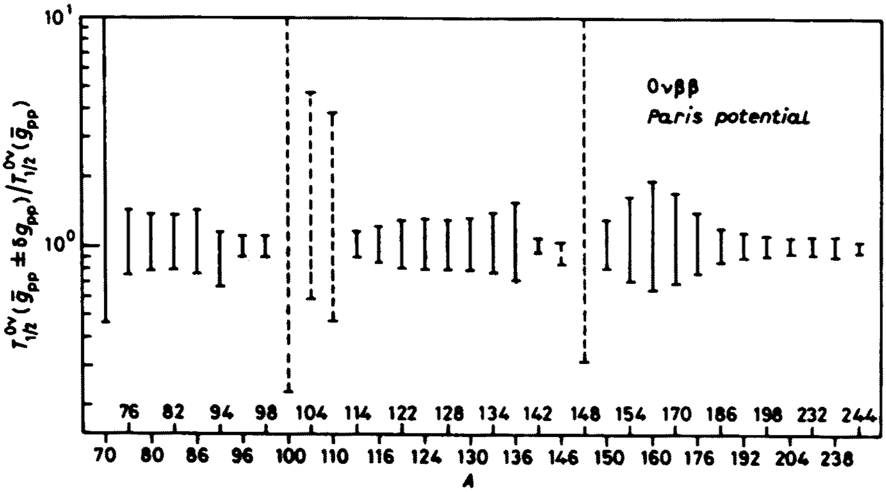


Figure 10: The uncertainty of QRPA-calculated $\beta\beta_{0\nu}$ rates originating from the limited knowledge of the particle-particle force for the potential double beta emitters (from [sta90b])

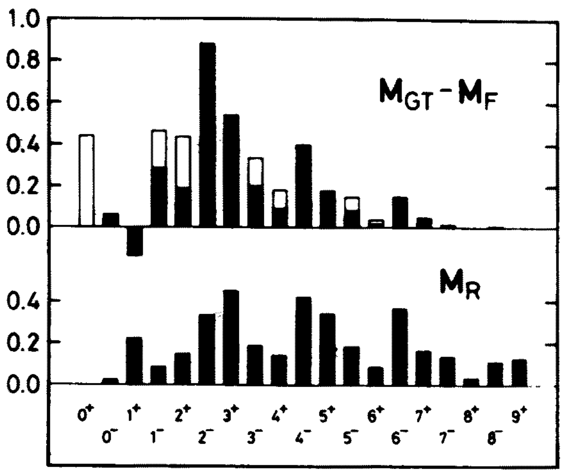


Figure 11: The decomposition of the nuclear matrix element $M_{GT}^{0\nu} - M_F^{0\nu}$ (upper) and M_R (lower) into contributions through intermediate states with spin parity J^π for the $\beta\beta_{0\nu}$ decay of ^{76}Ge$\rightarrow^{76}$Se. In the upper part, the contribution of $M_{GT}^{0\nu}$ and $-M_F^{0\nu}$ are denoted by the filled and open histograms, respectively (from [mut89])

states of different multipolarity J^π in the intermediate nucleus are excited. Figure 11 shows the decomposition of the nuclear matrix elements $M_{GT}^{0\nu} - M_F^{0\nu}$ and of the recoil matrix element M_R into contributions through intermediate states of different J^π. The total matrix element $M^{0\nu}$ remains relatively unaffected by g. s. correlations, because the latter affect mainly the 1^+ component. This reflects a well known feature of the nucleon-nucleon (proton-neutron) interaction: the pp interaction is strongly attractive in the $J^\pi = 1^+$ (the 0^+ and the highest multipole) channel, in other channels less attractive or slightly repulsive. It thus becomes clear why $\beta\beta_{0\nu}$ matrix elements can be predicted much more reliably than $\beta\beta_{2\nu}$ matrix elements. It has been also shown [sta90a, sta90c] that the calculated 0ν rates remain stable against different choices of the renormalized effective interaction, e. g. Bonn-A and Reid potentials instead of the Paris potential. The stability of the 0ν calculations against details of the wave functions reflects itself in rather close agreement of 0ν matrix elements calculated by different nuclear models (see, e.g. [gro90, kla92a]). A discrepancy occurs only when a not realistic interaction is used (as in [eng88]).

Concluding, nuclear structure seems to be understood well enough, not to limit $\beta\beta_{0\nu}$ decay to be the most powerful tool for probing the mass of the electron neutrino. Calculations of $\beta\beta_{0\nu}$ matrix elements are found for all $\beta^-\beta^-$ emitters in [gro85, gro86b, sta90b, hir92, wu92b], for $\beta^+\beta^+$ emitters in [sta91].

The problem of QRPA - some extreme dependence of the calculated rate on of $\beta\beta_{2\nu}$ the choice of the renormalization of the particle-particle force g_{pp}, seems recently to have been solved by applying the socalled operator expansion method (OEM) [wu91, hir92, wu92a, wu92b].

4.1.1 Calculation of $\beta\beta$ matrix elements by OEM

The method of OEM does not explicitely use the intermediate energy spectrum. This is the essential advantage over QRPA, since in this way the dependence on the *pp* force (which affects the distribution of β strength in the intermediate nucleus) is drastically reduced.

The method allows (by ignoring many-particle scattering terms) to write the matrix element for 2ν decay in the form

$$M_{GT} = \langle 0_F^+ | \sum_{i \neq j} \mathcal{M}_{ij} \tau_i^- \tau_j^- | 0_I^+ \rangle = M_0 + M_1 \, , \tag{22}$$

$$\mathcal{M}_{ij} = \frac{12\,(v_\sigma(r) - v_\tau(r))\,\Omega_0(ij)}{\Delta^2 - 16\,(v_\sigma(r) - v_\tau(r))^2} + \frac{4\,(2v_{\sigma\tau}(r) - v_\sigma(r) - v_\tau(r))\,\Omega_1(ij)}{\Delta^2 - 16\,(2v_{\sigma\tau}(r) - v_\sigma(r) - v_\tau(r))^2} \tag{23}$$

Thus the matrix element involves the bare nucleon-nucleon interaction without any adjustable parameter. The wave functions of initial and final states we take from QRPA. Figure 12 shows the results for ^{100}Mo and ^{238}U. The results for some other nuclei are given in [wu91], and calculations for all potential $\beta\beta$ emitters by this method are given in [hir92, wu92b]. Table 2 shows that the calculations in important cases give rather good agreement with experiment. Work on $\beta\beta_{0\nu}$ decay matrix elements using OEM shows that the results obtained are very close to those of QRPA. That the dependence on the *pp* force is overestimated by QRPA has been shown recently also by comparing QRPA and shell model for ^{48}Ca [mut91]. An essential over-simplification of QRPA is the projection of all types of correlations on spin-isospin correlations and changing them simultaneously in one and the same direction. It may be noted that the calculation of ^{238}U $\beta\beta$ decay by OEM, given in Table 2, was performed *before* the experimental result of [tur91] was known to us. The far-reaching conclusions drawn in that paper seem not to be on stable grounds.

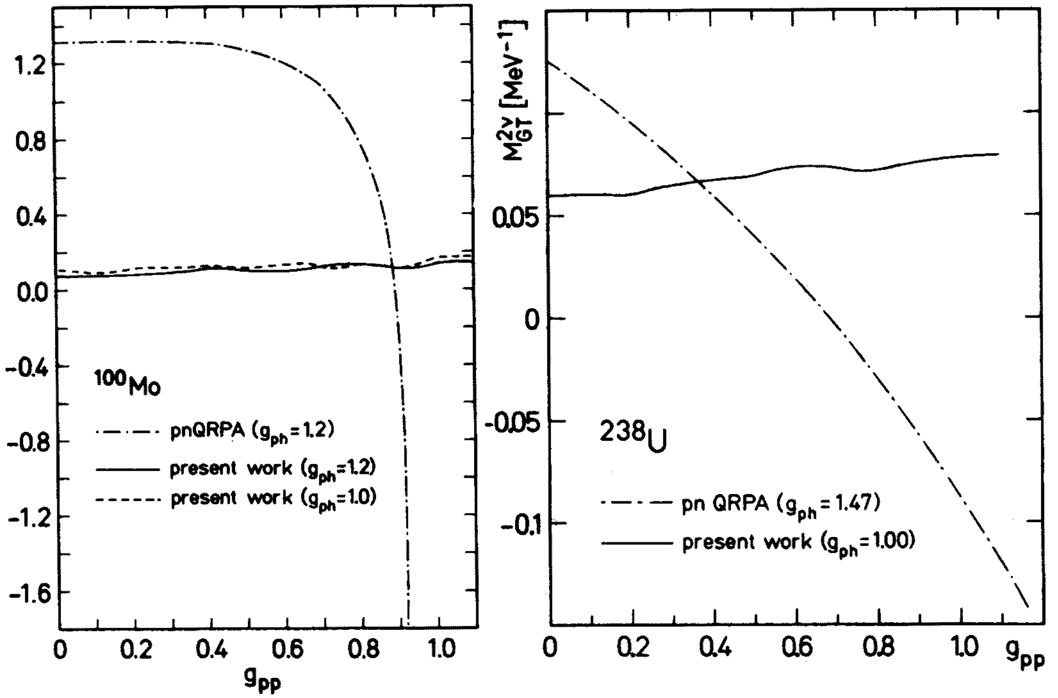


Figure 12: The matrix elements $M_{GT}^{2\nu}$ of $\beta\beta_{2\nu}$ decay of ^{100}Mo and ^{238}U as function of g_{pp} in QRPA and in OEM (from [wu91,wu92b])

Table 2: $2\nu\beta\beta$ Gamov-Teller elements and half-lives calculated by OEM [wu91,wu92b] and comparison with experiment

Nuclei	M_{GT} [MeV^{-1}]	half-life$_{theor}$ [years]	half-life$_{exp}$ [years]	
^{76}Ge	0.3351	$2.770 \cdot 10^{20}$	$(9.2^{+0.7}_{-0.4}) \cdot 10^{20}$ [a]	$1.42 \pm 0.2 \cdot 10^{21}$ [i]
^{82}Se	0.1019	$0.878 \cdot 10^{20}$	$(1.1^{+0.8}_{-0.3}) \cdot 10^{20}$ [b]	
^{100}Mo	0.1065	$3.370 \cdot 10^{19}$	$(1.15^{+0.30}_{-0.20}) \cdot 10^{19}$ [c]	$1.16 \cdot 10^{19}$ [d]
^{130}Te	0.1006	$0.937 \cdot 10^{20}$	$(1.5 - 2.8) \cdot 10^{21}$ [e,f]	$(0.75 \pm 0.03) \cdot 10^{21}$ [g,f]
^{238}U	0.0785	$0.914 \cdot 10^{21}$	$(2.0 \pm 0.6) \cdot 10^{21}$ [h]	

[a] [avi91], [b] [ell87], [c] [eji91], [d] [ell91], [e] [kir86]
[f] geochem. data (total $\beta\beta$ decay half-life), [g] [lin88], [h] [tur91], [i] [bec92a]

4.2 Double beta decay experiments

4.2.1 General status

The at present most extensively studied $\beta^-\beta^-$ emitters are shown in Fig.13. Figure 9 shows the shape of the expected spectra in the case of the detection of the summed kinetic energies of the two emitted electrons. The most important case of $\beta\beta_{0\nu}$ decay is obviously the experimentally most convenient one. The signal is a sharp line at an energy corresponding to the Q-value of the decay. The extremely low expected counting rates corresponding to half lifes of $T_{1/2} > 10^{24}$ years require extreme low-background conditions. Most experiments are therefore performed in underground laboratories to reduce the muon flux from cosmic radiation (Fig.14). Table 3 gives the conditions of μ flux and neutron flux for some of the most important laboratories. Figure 15 gives an overview over measured $\beta\beta_{0\nu}$ and $\beta\beta_{2\nu}$ half life limits or half lifes, Fig. 16 shows the neutrino mass limits deduced from the $\beta\beta_{0\nu}$ detector experiments (excluding geochemical experiments).

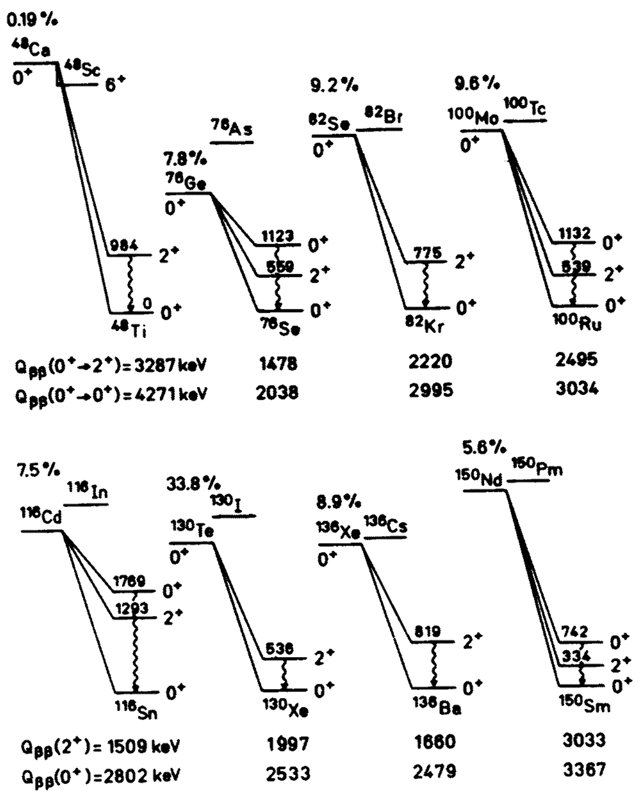


Figure 13: Some of the at present most studied $\beta\beta$ emitters

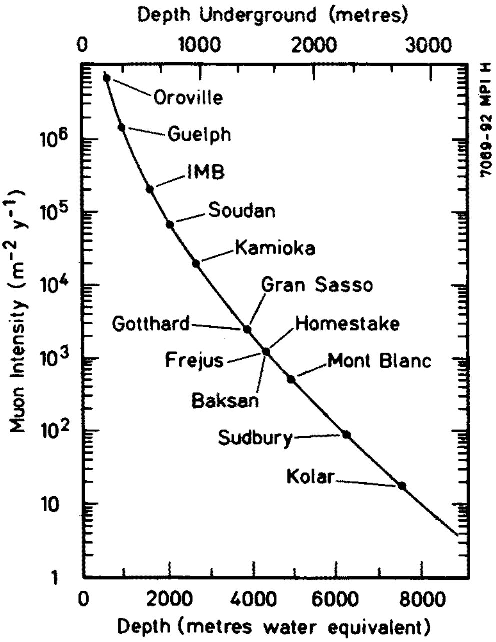


Figure 14: Some of the main underground laboratories, in which double beta decay experiments are performed, and their depth (in meter water equivalent) and reduction of cosmic radiation induced muon flux

Table 3: μ and n flux (without shielding) in some underground laboratories (from [zde92c])

Laboratory	depth [m.w.e.]	μ flux $m^{-2} \cdot d^{-1}$	n flux $cm^{-2} \cdot s^{-1}$
Mont Blanc	5000	0.7	$2.2 \cdot 10^{-5}$
Gran Sasso	3500	16	$5.3 \cdot 10^{-6}$
Frejus	4000	8	$< 3 \cdot 10^{-5}$
Broken Hill silver mine	3300	(20)	-
Solotvina salt mine	1000	$1.5 \cdot 10^3$	$< 2.7 \cdot 10^{-6}$
Baksan	660	$7 \cdot 10^3$	$3 \cdot 10^{-5}$
Windsor salt mine	650 (350m)	$(7 \cdot 10^3)$	-

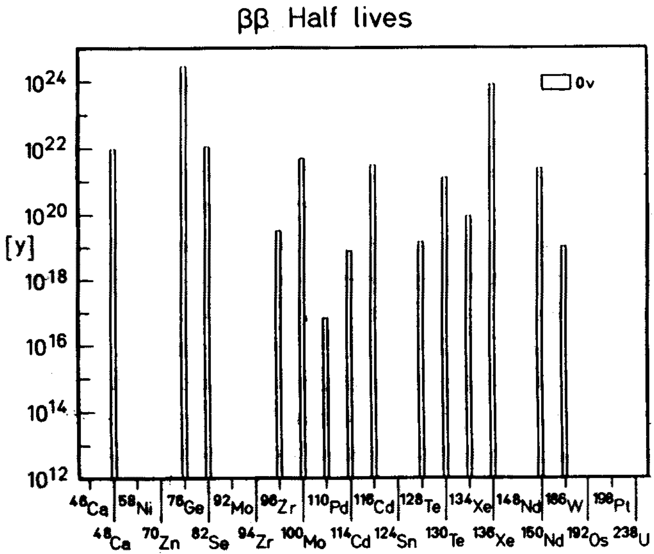


Figure 15: Measured $\beta\beta_{0\nu}$ half-life limits

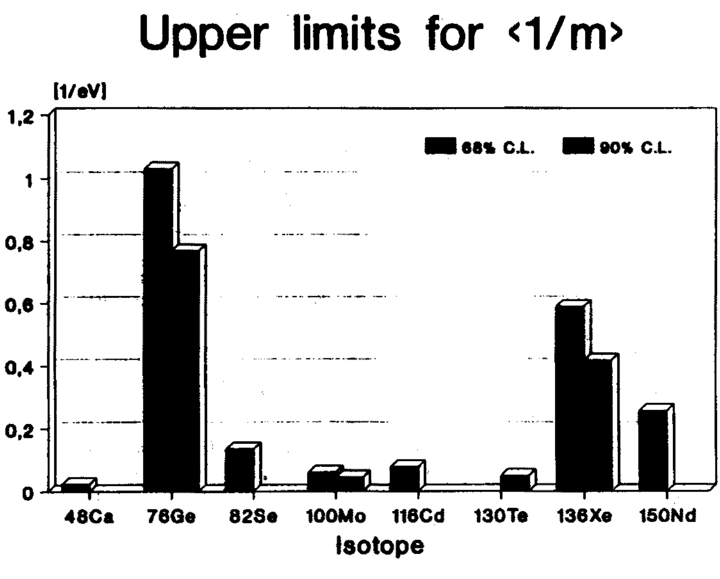


Figure 16: Neutrino mass limits deduced from $\beta\beta_{0\nu}$ detector experiments (i. e. *not* including geochemical experiments)

We can differentiate between two classes of direct (non-geochemical) $\beta\beta$ decay experiments (Fig. 17):

a) active source experiments (source=detector),

b) passive source experiments, which can be divided again into two kinds - with only measuring the energy of the electrons, or with tracking+energy detectors.

In the first class of experiments the $\beta\beta$ process usually is identified only on the basis of the distribution of the total energy of the electrons. The second class of experiments yields more complete information on the $\beta\beta$ events by measuring time coincidence, tracks and vertices of the electrons and their energy distribution. But also time projection chambers (TPCs) using $\beta\beta$ active counting gas are belonging to the first class - such as the Gotthard ^{136}Xe experiment.

It is obvious from Fig.15 that the largest sensitivity for $\beta\beta_{0\nu}$ decay is obtained by active source experiments, in particular ^{76}Ge [bal92, kla91a, kla92] and ^{136}Xe [won91, vui92] (only the geochemical experiment with ^{128}Te reaches a similar limit). The main reason is that large source strengths can be used (simultaneously with high energy resolution), in particular when enriched $\beta\beta$ emitter materials are used. The present best $\beta\beta_{0\nu}$ half life limits are better than 10^{24} years. On the other hand passive sources may be more promising in sensitivity for $\beta\beta_{2\nu}$ decay. While the best half life limit for neutrinoless $\beta\beta$ decay set by this type of experiment is 10^{22} y, the present level of sensitivity for $\beta\beta_{2\nu}$ decay is 10^{19-20} y.

Other criteria for the "quality" of a $\beta\beta$ emitter are:

- a small product $T^{0\nu}_{1/2} \cdot < m_\nu >^2$, i. e. a large matrix element $M^{0\nu}$,

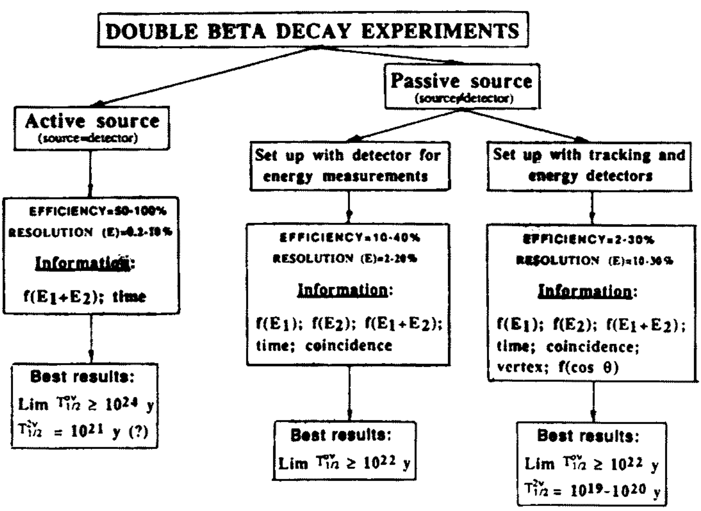


Figure 17: Classification of double beta decay experiments (after [zde92c])

- a $Q_{\beta\beta}$ value beyond the limit of natural radioactivity (2.614 MeV).

Table 4 lists some important $\beta\beta$ emitters according to these criteria. It is interesting to note that the differences in the matrix elements are surprisingly small.

While $\beta\beta_{2\nu}$ decay has been observed for a few isotopes (up to now: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{128}Te, ^{130}Te and ^{238}U), $\beta\beta_{0\nu}$ decay has not yet been seen experimentally.

We list some of the present activities and their perspectives.

Table 4: Some $\beta\beta$ emitters and their "qualities" according to the criteria of $Q_{\beta\beta}$ value and 0ν matrix element (the latter from [sta90b])

Nuclei	energy $Q_{\beta\beta}$ [MeV]	$T_{1/2}^{0\nu} \cdot \langle m_\nu \rangle$ [y·eV^2]
^{76}Ge	2.04	$2.3 \cdot 10^{24}$
^{82}Se	3.0	$6 \cdot 10^{23}$
^{96}Zr	3.3	$5.3 \cdot 10^{23}$
^{100}Mo	3.03	$1.3 \cdot 10^{24}$
^{116}Cd	2.8	$4.9 \cdot 10^{23}$
^{130}Te	2.53	$4.9 \cdot 10^{23}$
^{136}Xe	2.48	$2.2 \cdot 10^{24}$
^{150}Nd	3.37	$3.4 \cdot 10^{23}$

4.2.2 Present activities and their perspectives

Active sources

^{48}Ca: The Beijing group [key91] uses scintillator crystals of natural CaF_2, in total 37.4 kg, containing 43 g of ^{48}Ca. They report $T_{1/2}^{0\nu} > 9.5 \cdot 10^{21}$ y, which corresponds to $m_\nu < 42.4$ eV. A Moscow group from Kurchatov institute has 30 g of enriched ^{48}Ca available. There are plans to use this in form of a scintillation detector.

^{76}Ge: Experiments with natural detectors [cal90, reu92] have been surpassed by enriched detector setups. The first enriched Ge(Li) detectors (in total 1.3 kg) were operated in the Moscow-Erewan experiment [kir92a, vas90]. This experiment gave the best limit on the electron neutrino mass up to the end of 1991, when the Heidelberg-Moscow experiment [bal92, kla91a, kla91b, kla92, kla92a] with now 9.6 kg of enriched HP Ge-detectors took over (see next section). The present limit reached in the Heidelberg-Moscow experiment is $T_{1/2}^{0\nu} >$

$1.93 \cdot 10^{24}$ y (90 % C.L.) and $m_\nu < 1.10$ eV. After some years a limit of $T^{0\nu}_{1/2} > 10^{25}$ y ($m_\nu < 0.2$ eV) seems accessible. There is another experiment (IGEX) planning to use a similar amount of enriched ^{76}Ge under discussion and in preparation [kir92b, mor89, mor92].

^{116}Cd: At Kiev three enriched scintillation crystals of $^{116}CdWO_4$ (enriched in ^{116}Cd to 83 %) are in operation [zde91, zde92b]. The present limit is $T^{0\nu}_{1/2} > 10^{22}$ y ($m_\nu < 7$ eV). There is a project under discussion of a big scale experiment with $^{116}CdWO_4$ crystals (20 kg of ^{116}Cd), aiming at limits of $T^{0\nu}_{1/2} > 10^{25}$ y and $m_\nu < 0.3$ eV.

^{130}Te: Recently a cryogenic thermal ^{130}Te detector of 73 g has put into operation in the Gran Sasso laboratory [ale92, zan92]. After 876 h of operation a limit of $T^{0\nu}_{1/2} > 2 \cdot 10^{21}$ y ($m_\nu < 15$ eV) has been established. In future with enriched $^{130}TeO_2$ crystals of 1-2 kg a limit of $T^{0\nu}_{1/2} > 2 \cdot 10^{24}$ y ($m_\nu < 0.5$ eV) may be reached.

^{136}Xe: The most sensitive experiment here is the Gotthard experiment [won91, vui92], using a TPC of a volume of 207 l, operated at 5 atm with Xenon enriched in ^{136}Xe to 62.5%. This experiment reaches an extremely good background of 0.01 counts/y·kg·keV, and reports a limit of $T^{0\nu}_{1/2} > 4.1 \cdot 10^{23}$ y ($m_\nu < 2.3$ eV). With a major upgrading of the active mass of ^{136}Xe (to 8-10 kg) a limit of 10^{25} y and $m_\nu < 0.5$ eV might become accessible in some future. The Moscow experiment [art92] uses a proportional drift detector with 210 g of ^{136}Xe. The suggestion of Moe [moe91] to detect the energy signal in coincidence with the produced $^{136}Ba^{2+}$ ion in a liquid Xenon TPC may allow a further major improvement.

Passive sources

^{82}Se: ^{82}Se was the first isotope for which $\beta\beta_{2\nu}$ decay was observed in a non-geochemical experiment [ell87], using a TPC. The deduced limit for the $\beta\beta_{0\nu}$ half life is $T^{0\nu}_{1/2} > 1.1 \cdot 10^{22}$ y ($m_\nu < 7.4$ eV). This experimental setup is now used with ^{100}Mo.

^{96}Zr; For ^{96}Zr $\beta\beta_{0\nu}$ decay exist limits $T^{0\nu}_{1/2} > 3.0 \cdot 10^{19}$ y corresponding to $m_\nu < 133$ eV [zde81, nor87]. A new experiment using a kind of modified TPC is at present under construction [pov90, bud91] in a Bratislava-Dubna collaboration.

^{100}Mo: Five groups have made measurements with ^{100}Mo. The Kiev group used plastic scintillator wafer stacks with sheets of ^{100}Mo [zde82]. The same technique but with semiconductor (silicon) wafer stacks has been used by an LBL-MHC-UNM-INEL cooperation [als89].The obtained limits were $T^{0\nu}_{1/2} > 2 \cdot 10^{21}$ y and $T^{0\nu}_{1/2} > 4 \cdot 10^{21}$ y, respectively. A similar limit, $T^{0\nu}_{1/2} > 2.6 \cdot 10^{21}$ y, was

Table 5: Half-lives from different experiments and calculated upper limits for $\langle m_\nu \rangle$ (with matrix elements from [sta90b] and ignoring of right-handed weak interaction)

Nuclei	$T_{1/2}^{0\nu}$ [y]	$T_{1/2}^{2\nu}$ [y]	$\langle m_\nu \rangle$ [eV]	Ref.
^{46}Ca		* $> 5.4 \cdot 10^{12}$ (68%)		[frem50]
^{48}Ca	$> 9.5 \cdot 10^{21}$(76%)	$> 3.5 \cdot 10^{19}$ (80%)	$< 42.4^{\ddagger}$(76%)	[key91, bar70]
^{58}Ni		* $> 4.0 \cdot 10^{19}$ (90%)		[bel82]
^{70}Zn		* $> 2.0 \cdot 10^{15}$ (68%)		[frem50]
^{76}Ge	$> 3.2 \cdot 10^{24}$(68%) $> 1.9 \cdot 10^{24}$(90%)	$\approx 9.0 \cdot 10^{20}$ (68%) $1.42 \pm 0.2 \cdot 10^{21}$	< 0.86 (68%) < 1.1 (90%)	[mil90, vas90] [bec92a, bec92b]
^{82}Se	$> 1.1 \cdot 10^{22}$(68%)	$\left(1.1^{+0.8}_{-0.3}\right) \cdot 10^{20}$ (68%)	< 7.4 (68%)	[ell87]
^{92}Mo		* $> 6.0 \cdot 10^{18}$ (90%)		[bel82]
^{94}Zr		* $> 1.3 \cdot 10^{19}$ (68%)		[nor87]
^{96}Zr	$> 3.0 \cdot 10^{19}$(68%)	* $> 2.0 \cdot 10^{18}$ (68%)	< 133 (68%)	[zde81, nor87]
^{100}Mo	$> 4.7 \cdot 10^{21}$(68%) $> 2.6 \cdot 10^{21}$(90%)	$\left(1.15^{+0.30}_{-0.20}\right) \cdot 10^{19}$(68%) $\left(1.15^{+0.54}_{-0.28}\right) \cdot 10^{19}$(90%)	< 16.5 (68%) < 22.1 (90%)	[eji91b] [eji91b]
^{110}Pd	$> 6.0 \cdot 10^{16}$(68%)	$> 6.0 \cdot 10^{16}$ (68%) * $> 6.0 \cdot 10^{17}$ (68%)	< 5716 (68%)	[bar87] [win52]
^{114}Cd	$> 7.0 \cdot 10^{18}$(90%)		< 2692 (90%)	[mit88]
^{116}Cd	$> 3.0 \cdot 10^{21}$(68%)	$> 4.5 \cdot 10^{18}$ (90%)	< 12.8 (68%)	[zde91]
^{124}Sn		* $> 2.4 \cdot 10^{18}$ (68%)		[nor87]
^{128}Te	$> 7.7 \cdot 10^{24}$(90%)	* $(7.7 \pm 0.4) \cdot 10^{24}$	< 1.0 (90%)	[kir86, mit88, chi88, ber92a]
^{130}Te	$> 1.5 \cdot 10^{21}$(68%)	* $(2.7 \pm 0.1) \cdot 10^{21}$	< 18 (90%)	[zde80, kir86, chi88, ber92a]
^{134}Xe	$> 8.2 \cdot 10^{19}$(68%)	$> 1.1 \cdot 10^{16}$ (68%)	< 454 (68%)	[art92]
^{136}Xe	$> 7.8 \cdot 10^{23}$(68%) $> 4.1 \cdot 10^{23}$(90%)	$> 9.3 \cdot 10^{19}$ (90%) $> 6.0 \cdot 10^{19}$ (90%)	< 1.7 (68%) < 2.4 (90%)	[won92, art92] [won92, art92]
^{148}Nd		* $> 2.7 \cdot 10^{18}$ (90%)		[bel82]
^{150}Nd	$> 2.3 \cdot 10^{21}$(68%)	$> 2.4 \cdot 10^{19}$ (68%)	< 3.9 (68%)	[kli86b]
^{186}W	$> 9.0 \cdot 10^{18}$(68%)		< 840 (68%)	[dan89]
^{192}Os		* $> 1.3 \cdot 10^{13}$ (68%)		[frem50]
^{198}Pt		* $> 5.7 \cdot 10^{14}$ (68%)		[frem50]
^{238}U		* $\left(2.0^{+0.6}_{-0.6}\right) \cdot 10^{21}$ (68%)		[tur91]
^{244}Pu		* $> 1.1 \cdot 10^{18}$ (68%)		[moo92]

*measurement of $T_{1/2}^{0\nu+2\nu}$ (geochem. or chem. method)

‡calculated by use of [mut91] set by the Osaka group [eji91a, eji91b], who use drift chambers and plastic scintillators. The Irvine ^{100}Mo experiment [ell91] uses a TPC with 8.3 g of enriched $^{100}MoO_3$. They report up to now only a half life for 2ν decay of $T^{2\nu}_{1/2} = 1.16^{+0.34}_{-0.08} \cdot 10^{19}$ y. The Kiev-Orsay experiment (NEMO collaboration) [cam92, zde92a, zde92b] has built up a set of 2×64 plastic scintillators and uses 300 g of natural Mo foil. Use of 500 g of enriched (99.5 %) ^{100}Mo is planned for 1992 in a set-up NEMO II. The long-term plan is the use of 5 kg of enriched ^{100}Mo in a NEMO III setup aiming at limits of $T^{0\nu}_{1/2} > 10^{25}$ y ($m_\nu < 0.4$ eV). Until this aim could be reached, however, very serious technological problems wait for their solution.

The $\beta\beta$ decays of ^{82}Se, ^{128}Te and ^{130}Te have been investigated also by geochemical methods, which can measure only the "sum" of 0ν and 2ν decay rates. For a recent review we refer to [man91]. The recently measured (0ν + 2ν)-half-life for ^{128}Te [ber92a] yields together with the Heidelberg-Moscow ^{76}Ge experiment at present the sharpest limits on the neutrino mass (Table 5). The sensitivity of the geochemical experiments can, however, in contrast to the detector experiments not be increased, since they cannot investigate the 0ν channel separately. By chemical methods also recently the decays of ^{238}U [tur91] and ^{244}Pu [moo92] have been investigated. Table 6 lists up the present experiments.

Because of its particular scientific potential for the next years let us briefly look in some more detail into the Heidelberg-Moscow experiment.

THE HEIDELBERG-MOSCOW EXPERIMENT USING ENRICHED ^{76}GE The HEIDELBERG-MOSCOW $\beta\beta$ experiment [bal92, kla92] makes use of 16.9 kg of ^{76}Ge metal enriched to 86%, corresponding to 14.5 kg of the isotope ^{76}Ge. The full amount of ^{76}Ge has been transfered from Moscow to Heidelberg. Up to now one enriched detector of ≈1 kg, another of 2.9 kg (the largest ever produced Ge detector at that time) and another two detectors of 2.5 and 2.9 kg have been produced. The first detector is running in the *Gran Sasso Underground Laboratory* in Italy since end of July 1990, the second since September 1991 and the third since September 1992. Two more will be installed in the course of next year. Figure 18 shows the HEIDELBERG-MOSCOW $\beta\beta$ laboratory built generously by the INFN in the Gran Sasso, Fig.19 shows the first enriched detector in its shielding, and the 3.5 kg enriched ^{76}Ge crystal, from which the first 2.9 kg detector was made.

The total mass of enriched ^{76}Ge in form of detectors of about 9.6 kg (including a small 0.3 kg detector) corresponds to a non-enriched Ge experiment of about 1.2 tons (in the largest natural Ge experiments [cal90, reu92] about 8 kg were used).

Enrichment is the most efficient way of increasing the sensitivity of a $\beta\beta$ experiment of this kind. The half-life limit $T_{1/2}$ [y] to be extracted from the background fluctuation if no peak is present after measuring time t [y], is:

$$T_{1/2} > \left(4.18 \times 10^{24} \mathrm{kg}^{-1}\right) \frac{a}{f} \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \qquad (24)$$

where a: isotopical abundance of ^{76}Ge, M: active mass od the detector [kg], B: average background at the energy of the peak [counts/keV·y·kg], ΔE: energy resolution (FWHM) [keV]. The factor f connects the limit to a confidence level (C.L.); f=3.62 (1.35) for 90 (68)% C.L. if the minimum detectable count rate is estimated.

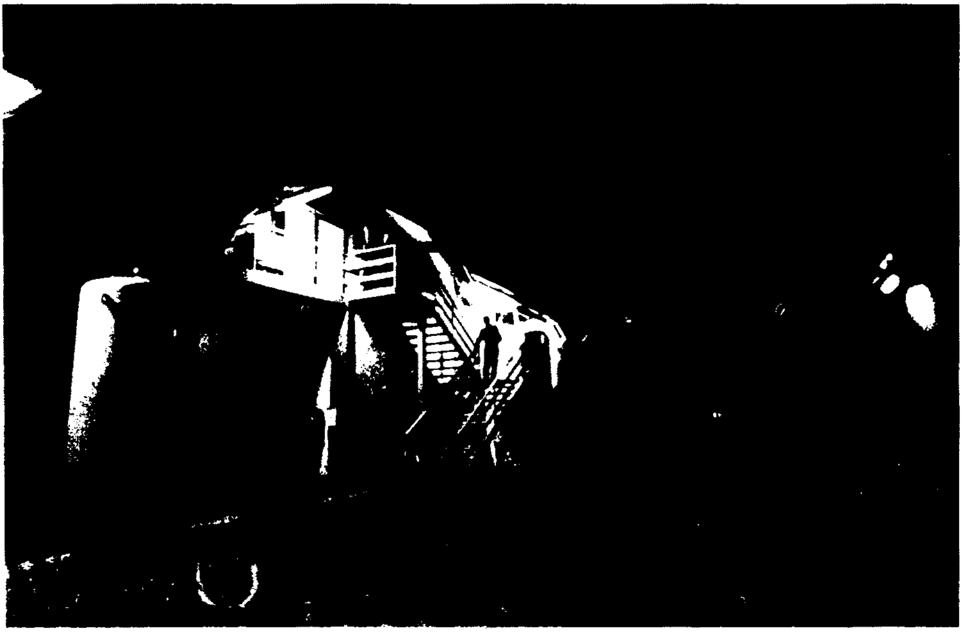


Figure 18: The $\beta\beta$ laboratory of the HEIDELBERG-MOSCOW experiment in the Gran Sasso near Rome

The enrichment factor a is the only parameter not connected through the square root to the sensitivity.

The results of the first 1133 kg·d of measuring with the first two detectors are:

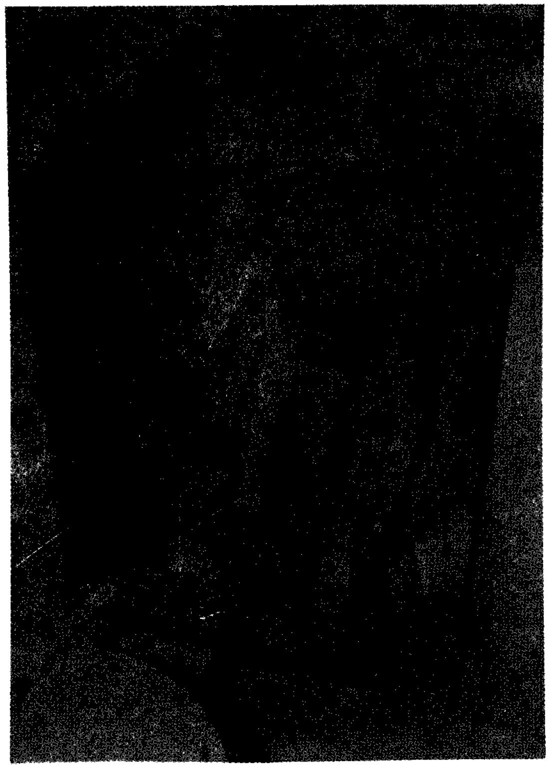
$0\nu\beta\beta$ decay $(0^+ \rightarrow 0^+)$:

$$\begin{aligned} T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) &> 1.93 \cdot 10^{24} y\,(90\% C.L.) \\ &> 3.21 \cdot 10^{24} y\,(68.3\% C.L.) \end{aligned} \tag{25}$$

The corresponding limits for the neutrino mass are

$$\begin{aligned} \langle m_\nu \rangle &< 1.10 eV\,(90\% C.L.) \\ &< 0.86 eV\,(68.3\% C.L.) \end{aligned} \tag{26}$$

The HEIDELBERG-MOSCOW experiment thus yields now the most stringent limit for the $\beta\beta_{0\nu}$ half-life of ^{76}Ge and the sharpest limit for the neutrino mass from detector experiments (compare Tables 5,6). The background level which characterizes the quality of the setup is 0.36 events/kg·y·keV (Fig.20) in an 80 keV interval around the



3.5kg ^{76}Ge Kristall

Figure 19: The worldwide first enriched HP-^{76}Ge detector (with Si cup) in its extreme low-level shielding, and the 3.5 kg ^{76}Ge crystal before transformation to the first 2.9 kg enriched detector

Table 6: N: source strength (amount of decaying isotope; B: average background at the decay energy in units of the amount of the decaying isotope; FWHM: energy resolution at the decay energy; t: measuring time; [a]: ^{76}Ge experiments; [b]: ^{136}Xe experiments; $\langle m_\nu \rangle$: effective Majorana mass; $\langle \eta \rangle$ ($\langle \lambda \rangle$): effective left-right-handed (right-right-handed) admixture to the weak interaction

Experiment	a	N [mol]	$N \cdot t$ [mol·y]	B $[\frac{C}{\text{keV}\cdot\text{y}\cdot\text{mol}}]$	FWHM [keV]	$T_{1/2}$ [10^{24} y]	$\langle m_\nu \rangle$ [eV] $\langle \eta \rangle \cdot 10^8$ $\langle \lambda \rangle \cdot 10^6$
[a] Caltech-Neuchâtel-PSI [boe91]	0.078	6.3	10.7	2.2	3.1	0.33	3.1 3.1 4.8
[a] UCSB-LBL [cal90]	0.078	7.3	22.6	1.1	3.3	1.2 (0.8)*	1.7 (2.0) 1.6 (2.0) 2.6 (3.1)
[a] Jerevan-ITEP [vas90]	0.85	13.3	14.5	0.19	3.7	1.0	1.8 1.8 2.8
[a] Heidelberg-Moscow [bal92]	0.86	68.8	30.2	0.036	3.5	1.9	1.3 1.3 2.0
[b] Milano [bel91]	0.64	20.7	14.6	2.2	124.0	0.02	11.7 8.6 15.8
[b] Caltech-Neuchâtel PSI [won91]	0.63	26.6	10.3	0.002	164.0	0.25	3.3 2.5 4.5

* if the remeasured decay energy is taken into account [vas90] obtain this result

hypothetical 2038.5 keV $\beta\beta_{0\nu}$-line for the total spectrum, and 0.29 events/kg·y·keV for the 2.9 kg detector.

$0\nu\beta\beta$ decay $(0^+ \rightarrow 2^+)$:

There is also no indication of a $\beta\beta$ transition to the first excited state of ^{76}Se which should occur at 1479.5 keV. We deduce a half-life limit

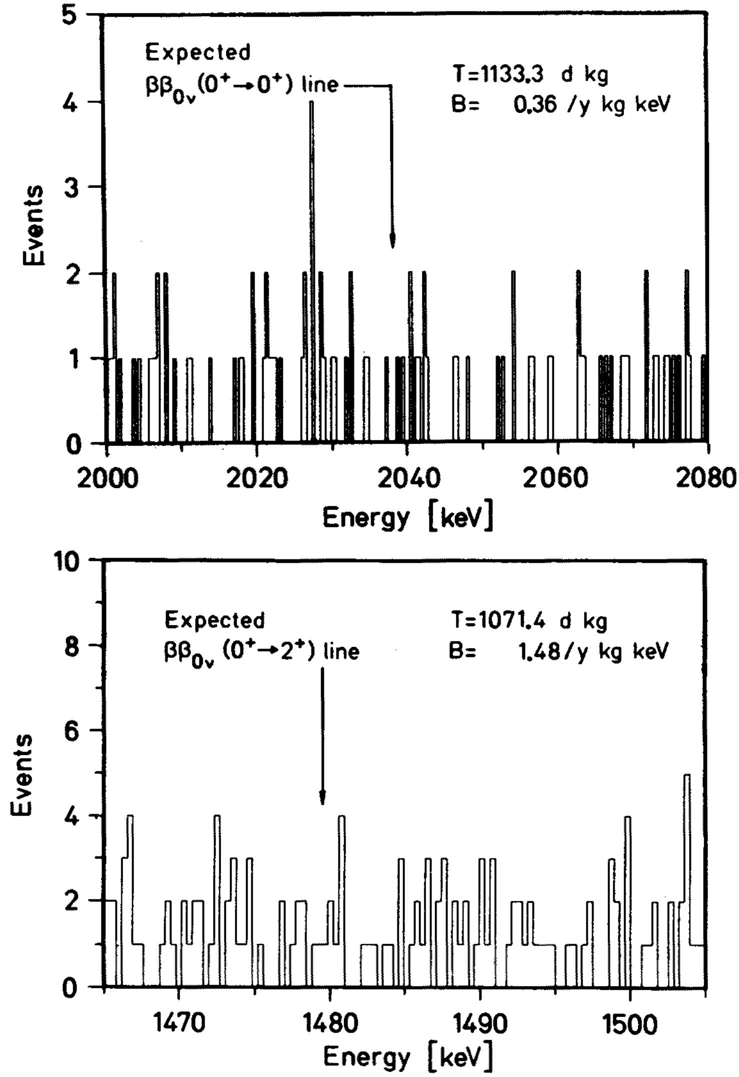


Figure 20: Details of the spectrum of the HEIDELBERG-MOSCOW collaboration in the region of neutrinoless double beta decay to the ground (upper part) and first excited (lower part) state of the daughter nucleus after a measuring time of 1133/1071 kg·d

$$T^{0\nu}_{1/2}(0^+ \to 2^+) > 7.98 \cdot 10^{23} y\,(90\% C.L.)$$
$$> 1.49 \cdot 10^{24} y\,(68.3\% C.L.) \qquad (27)$$

i. e. far beyond the half-life of $2.5 \cdot 10^{22}$ y claimed by [bus90].

$2\nu\beta\beta$ decay:

Careful subtraction of background contributions (from cosmogenically produced isotopes, natural decay chains and ^{210}Pb, for details see [bec92a, bec92b]) from the spectrum measured with the second detector in 527 kg·d yields the spectrum shown in Fig.21 and

$$T^{2\nu}_{1/2}(0^+ \to 0^+) = (1.42 \pm 0.2) \cdot 10^{22} y$$

This is the clearest evidence for this decay mode (compare [vas90, mil90, kir92a].

$0\nu\chi$ decay:

Subtracting from the solid spectrum in Fig.21 further the 2ν spectrum leads to the spectrum shown in Fig.22. This yields an upper limit for the $0\nu\chi$ decay mode of [bec92a]

$$T^{0\nu\chi}_{1/2} > 3.89 \cdot 10^{22} y\,(90\% C.L.)$$
$$> 4.08 \cdot 10^{22} y\,(68.3\% C.L.) \qquad (28)$$

For the neutrino-majoron coupling constant this leads to

$$\langle g_{\nu\chi} \rangle < 1.10 \cdot 10^{-4}\,(90\% C.L.) \qquad (29)$$

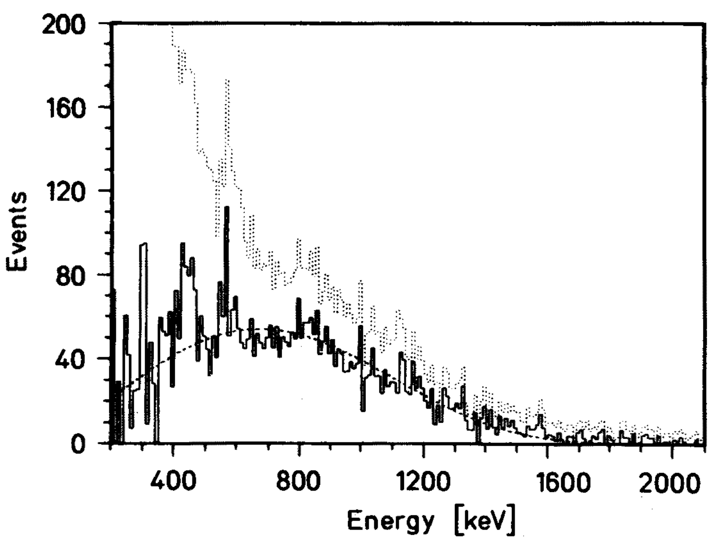


Figure 21: Comparison of the 527 kg·d measured spectrum (dotted curve, lines cut out) and after the subtraction described in the text (solid curve). Also shown is a fitted 2ν-spectrum for $T^{2\nu}_{1/2} = 1.42 \cdot 10^{21} y$ (dashed curve)

The HEIDELBERG-MOSCOW experiment thus yields already with only part of its final ^{76}Ge source strength the sharpest limit for $0\nu\chi\beta\beta$ decay (see Table 7). It excludes some recently discussed [moe92] indications for this decay mode.

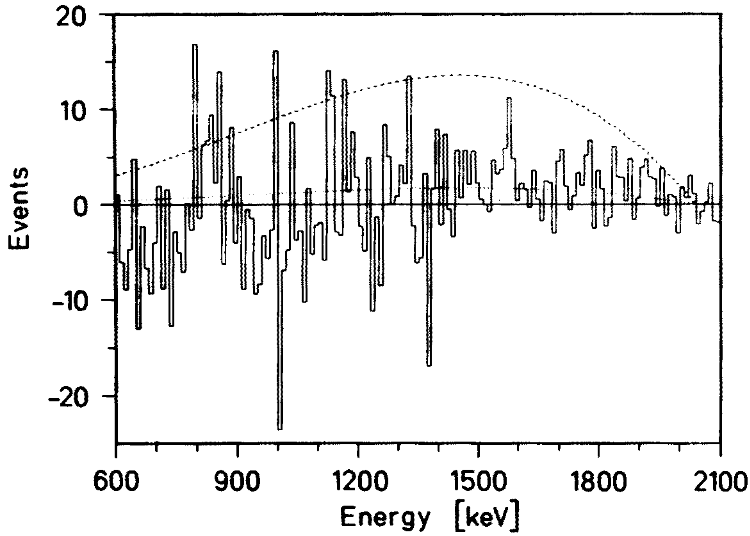


Figure 22: Remaining spectrum after further subtracting from the solid curve in Fig.21 the 2ν mode, together with a calculated $0\nu\chi$ spectrum with $T_{1/2}^{0\nu\chi} = 3.89 \cdot 10^{22}y$ (dotted curve). The recently discussed [moe92] coupling constant of $3 \cdot 10^{-4}$ would yield the dashed curve

Table 7: Half-life limits for the $0\nu\chi$ decay and the corresponding limits for the neutrino-majoron coupling constant for several isotopes.

Isotope	Experiment	$T_{\frac{1}{2}}(\cdot 10^{21}y)$	$< g_{\nu\chi} > (\cdot 10^{-4})$	Reference
^{76}Ge	MPIK-KIAE	38 (90 %)	1.1	[bec92a]
^{76}Ge	ITEP	10 (68 %)	2.2	[vas90]
^{76}Ge	UCSB-LBL	1.4 (90 %)	5.8	[cal87]
^{76}Ge	PNL-USC	6.0	2.8	[avi86]
^{76}Ge	Cal.-PSI -Neu.	1.0 (90 %)	6.9	[fis89]
^{100}Mo	LBL-MHC-UNM	0.33 (90 %)	6.2	[als88]
^{136}Xe	ITEP	0.19 (68 %)	12.5	[bar90]
^{136}Xe	Cal.-PSI-Neu.	7.2 (90 %)	2.0	[vui92]
^{82}Se	UCI	1.6 (68 %)	12.5	[ell87]
^{150}Nd	INR	0.07 (68 %)	1.9	[kli84]
^{48}Ca	ITEP	0.72	5.1	[bar89]

Electron decay:
The limit obtained as a by-product of the $\beta\beta$-experiment for the decay mode

$$e^- \rightarrow \gamma + \nu_e \tag{30}$$

after 368 kg·d of measurement with the second enriched detector is [bec92b]

$$T_{1/2}(e^- \rightarrow \gamma + \nu_e) > 1.63 \cdot 10^{25} y \, (68\% C.L.) \tag{31}$$

The best limits up to now were $T_{1/2} > 1.0 \cdot 10^{25} y$ for this mode [avi86a] and $T_{1/2} > 1.9 \cdot 10^{23} y$ for the decay mode $e^- \rightarrow \nu_e + \nu_e + \overline{\nu}_e$ [reu91]. Fig.23 shows the spectrum after 368 kg·d in the range of the 255 keV γ-line expected from a decay $e^- \rightarrow \gamma + \nu_e$.

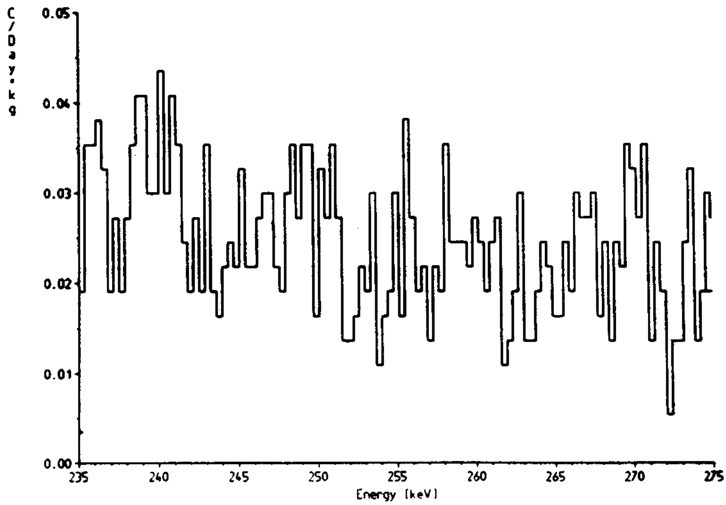


Figure 23: Spectrum measured in 368 kg·d in the range of the 255 keV γ-line expected from a decay $e^- \rightarrow \gamma + \nu_e$

The experiment also allows - like other sensitive $\beta\beta_{0\nu}$ experiments - a comment to the hypothetical 17 keV neutrino. Such a neutrino with the claimed admixture of $\sim$ 1% to the ν_e flavor [nor91] would lead to a signal in our $\beta\beta_{0\nu}$ spectrum corresponding to an electron neutrino mass of ~100 eV. We exclude on the other hand masses $\geq$1 eV. $\beta\beta$ experiments thus clearly exclude 17 keV Majorana neutrinos.

The perspectives of the experiment - and the improvement compared to the best non-enriched experiment (UCSB-LBL) - are shown in Fig.24. After five years of measurement we hope to come close to the limit of ~0.1 eV for the electron neutrino mass.

Finally it should be pointed out that modern $\beta\beta$ techniques which showed for the first time that the technology of high-purity enriched Ge detectors can be handled, seems to find important applications in new generation high-resolution γ-ray astronomy with balloons and satellites by using enriched ^{70}Ge instead of natural detectors. It also allows considerable improvement in the search for dark matter

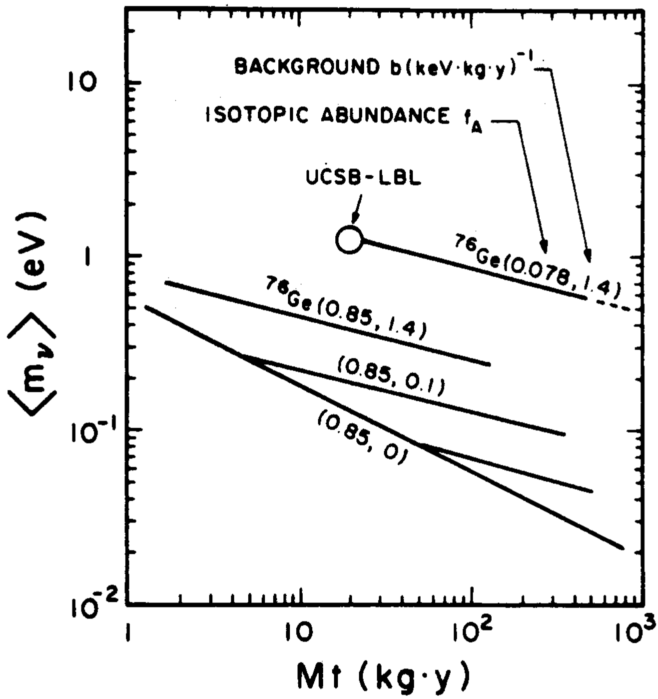


Figure 24: The ranges of neutrino mass which can be probed with Ge-detectors of different enrichment in ^{76}Ge, as function af the product detector mass times measuring time (kg·y) (from [moe91])

(WIMPs), not only with ^{76}Ge (spin 0) detectors but particularly when enriched ^{73}Ge detectors (spin $\neq 0$) are used. We refer for those applications to [kla91d].

4.2.3 Future of $\beta\beta$ decay

If we look into the future of $\beta\beta$ decay experiments we may have the following classification:

1. The "immediate" future (next five years) will be dominated by *active enriched* detectors, the most promising $\beta\beta$ emitters being ^{76}Ge, ^{136}Xe and ^{116}Cd, the most advanced experiments in this direction being the Heidelberg-Moscow (^{76}Ge) and Gotthard (^{136}Xe) experiment followed by the Kiev (^{116}Cd) plan. These experiments can be expected to reach neutrino mass limits of $\sim$ 0.2, 0.7 and 0.3 eV (in this order) in several years. In particular ^{136}Xe may have large potential for a very large mass experiment [gir92, moe91]. Among the passive sources the Kiev-Orsay experiment NEMO II [zde92a, zde92b] aiming at use of 5 kg of enriched ^{100}Mo in a set-up of plastic scintillators with sheets of ^{100}Mo might be particularly mentioned.

2. In longer term future (> 5 years) cryogenic detectors [giu91, mös91, cal91b] may play an important role. A first cryogenic calorimetry detector (where the

excess phonons generated by the incident radiation cause a temperature change of the absorber) for investigation of $\beta\beta$ decay has been operated by the Milano group [giu91, zan92]. They operate a 72 g TeO_2 cryogenic crystal to search for $\beta\beta$ decay of ^{130}Te, with an energy resolution of about 10 keV at 1.3 MeV. In future with enriched $^{130}TeO_2$ crystals of 1-2 kg a limit of $T_{1/2}^{0\nu} > 2 \cdot 10^{24}$ y ($m_\nu \leq 0.5$ eV) may be reached. It should be pointed out that the cryogenic technique could be applied to a large range of crystals containing double beta emitters.

3. For the further future superheated superconducting granules (SSG) may become of interest in $\beta\beta$ decay. Here however quite formidable technical problems still wait for a final solution [prez90]. Also new approaches taking advantage of previously unexploited features of $\beta\beta$ decay may be promissing, like coincident detection of $^{136}Ba^{2+}$ ions (detected by its laser fluorescence) together with the 2.5 MeV $\beta\beta$ energy pulse from decay of ^{136}Xe in a liquid Xenon TPC [moe91]. A background-free 1000 kg of ^{136}Xe could probe an effective Majorana mass for the electron neutrino of $\sim$ 0.01 eV in five years of running.

5 Conclusion

Among the various experimental approaches to measure the (electron) neutrino mass double beta decay at present yields the sharpest limits. A new era of second generation experiments, using active detectors made from enriched material is starting at present in double beta decay research. This technique will allow to reach a limit of $\approx$0.1 eV for the neutrino mass in a few years. At the same time it has major impact on high-resolution γ-ray line astrophysics with balloons and satellites. Further improvements would require new experimental approaches which would need considerably larger time scales.

Recent results of the GALLEX collaboration on the solar neutrino flux [ans92] make $\beta\beta$ experiments even more attractive, since they disfavor a magnetic moment of the neutrino, thus favoring its Majorana nature. Also the MSW mechanism of neutrino oscillations may not be needed to explain their result, which would with some common assumptions on a mass hierarchy of the neutrino flavors have put the electron neutrino mass in a $\sim 10^{-5}$ eV range or so. In other words, solar neutrinos do not seem to allow probing of neutrino masses in this mass range. This makes it even more challenging and more important to improve the possibilities of double beta decay experiments.

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