MeV neutrinos in double beta decay

K. ZUBER

Lehrstuhl für Exp. Physik IV, Universität Dortmund, Otto-Hahn-Str. 4,
44221 Dortmund, Germany

Abstract

The effect of Majorana neutrinos in the MeV mass range on the double beta decay of various isotopes is studied on pure phenomenological arguments. By using only experimental half life data, limits on the mixing parameter U_{eh}^2 of the order 10^{-7} can be derived. Also the possible achievements of upcoming experiments and some consequences are outlined.

One of the major challenges of modern physics is the still open question of a nonzero neutrino mass. A massive neutrino could have important consequences for astrophysics and cosmology, i.e. massive neutrinos are good dark matter candidates and massive neutrinos are the preferred solution of the solar neutrino problem via the MSW-effect. From the particle physics point of view massive neutrinos would require a modification of the successful standard model and would open one of the most promising ways for testing models beyond the standard model (GUT-theories). For the physical potential of massive neutrinos see [1].

Direct measurements of neutrino masses result at present in limits for the three neutrinos of

$$m_{\nu_e} \quad < \quad 4.35 \quad eV \quad \text{(out of tritium beta decays [2])}, \tag{1}$$

$$m_{\nu_\mu} \quad < \quad 160 \quad keV \quad \text{(out of pion-decays [3])} \tag{2}$$

$$m_{\nu_\tau} \quad < \quad 24 \quad MeV \quad \text{(out of tau-decays [4])} \tag{3}$$

As can be seen MeV τ-neutrinos are not ruled out at present. In recent times there is a growing interest in models with MeV τ-neutrinos [5]. To be cosmological acceptable such neutrinos must be unstable because otherwise they will overclose the universe. On the other hand bounds on the number of neutrino flavours coming out of big bang nucleosynthesis have been relaxed recently, now allowing a value between about 2.2 [6] and 3.9 [7]. This opens space for a MeV-mass of ν_τ.

In this paper the effects of a MeV Majorana-neutrino in double beta decay are investigated. For a discussion of heavy sterile neutrinos in double beta decay see [8]. The analysis follows partly that of [9, 10]. Neutrinoless double beta decay ($0\nu\beta\beta$ decay) of a nucleus (A,Z)

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- \tag{4}$$

violates lepton number by 2 units and is only possible if neutrinos are Majorana particles (see [1]). There are about 35 possible double beta decay emitters, about 10 of them have experimental obtained half life limits of larger than 10^{20}y. At present the best limit results from the Heidelberg-Moscow collaboration studying the decay of ^{76}Ge [11]

$$T_{1/2}^{0\nu} > 7.4 \cdot 10^{24} a \rightarrow <m_{\nu_e}> \, < 0.56 \quad eV \quad (90\% \quad CL) \tag{5}$$

The measured quantity (neglecting right handed weak currents), called effective Majorana mass $< m_{\nu_e} >$, is given in the case of light neutrinos ($m_\nu < 1$ MeV) by

$$< m_{\nu_e} > =| \sum_{i=1}^{N} U_{ei}^2 m_i | \tag{6}$$

where m_i characterizes the N mass eigenstates and U_{ei} the mixing matrix elements. Things change in case of heavy neutrinos ($m_\nu > 1$ MeV). By calculating the nuclear matrix elements for double beta decay involving MeV neutrinos the neutrino mass in the neutrino propagator can no longer be neglected with respect to the neutrino momentum. For a detailed discussion on the matrix element calculations see [12]. This results in a change of the radial shape of the used neutrino potential H(r) from

$$H(r) \propto \frac{1}{r} \quad \text{light neutrinos} \ \rightarrow H(r) \propto \frac{exp(-m_h r)}{r} \quad \text{heavy neutrinos} \tag{7}$$

This changes can be accomodated for by introducing an additional factor $F(m_h, A)$ in eq. (6), which depends on the mass of the heavy neutrino m_h and on the atomic number A of the nucleus. Eq. (6) is modified to

$$< m_{\nu_e} > =| \sum_{i=1,light}^{N} U_{ei}^2 m_i + \sum_{h=1,heavy}^{M} F(m_h, A) U_{eh}^2 m_h | \tag{8}$$

Assuming one heavy neutrino with $m_h = m_2$ the function $F(m_h, A)$ is given by

$$F(m_2, A) =< 1/r >^{-1}< exp(-m_2 r)/r > \tag{9}$$

r corresponds to the distance of the two nucleons in the nucleus undergoing $0\nu\beta\beta$ decay . The average is with respect to the two nucleon correlation function appropriate for the nucleus. Using a correlation function containing a hard core repulsion characterized by a hard core radius r_c of 0.5 fm between the two nucleons

$$\rho(r) = \frac{1}{4/3\pi[(2R)^3 - r_c^3]}\theta(r - r_c)\theta(2R - r) \tag{10}$$

it follows

$$F(m_2, A) = 0.5\frac{1}{(m_2 R)^2}[(1 + m_2 r_c)exp(-m_2 r_c) - (1 + 2m_2 R)exp(-2m_2 R)] \tag{11}$$

For all nuclei of interest ($A \geq 48$) the nuclear radius R is much larger than the hard core radius ($R \gg r_c$). Therefore $F(m_2, A)$ varies with the nuclear radius as R^{-2} or using the relation $R \simeq 1.2A^{1/3}$ fm it results in a dependence of $A^{-2/3}$.

Consider now the simple case of an electron coupled via the standard weak charged current to two massive Majorana neutrinos $\chi_{1,2}$ under the assumption of CP-conservation:

$$\nu_e = \chi_1 cos\theta + \chi_2 sin\theta \tag{12}$$

where the fields $\chi_{1,2}$ satisfy the Majorana condition (C is the charge conjugation matrix):

$$\chi_{1,2} = \eta_{1,2}C\bar{\chi}_{1,2} \quad \eta_i = \pm 1 \tag{13}$$

The corresponding $< m_{\nu_e} >$ is then given as

$$< m_{\nu_e} > =| m_1 cos^2\theta + \eta_1\eta_2 m_2 sin^2\theta | \tag{14}$$

2

in the case of only light neutrinos or for one light and a MeV-neutrino as

$$< m_{\nu_e} > =| m_1 cos^2\theta + F(m_2, A)\eta_1\eta_2 m_2 sin^2\theta | \qquad (15)$$

In case of small mixing angles θ the β-decay experiments measure m_1. For double beta decay if $\theta \neq 0$ and $\eta_1\eta_2 = -1$ something like destructive interference can occur in $< m_{\nu_e} >$ and the value measured can be smaller than the one from the tritium experiments.
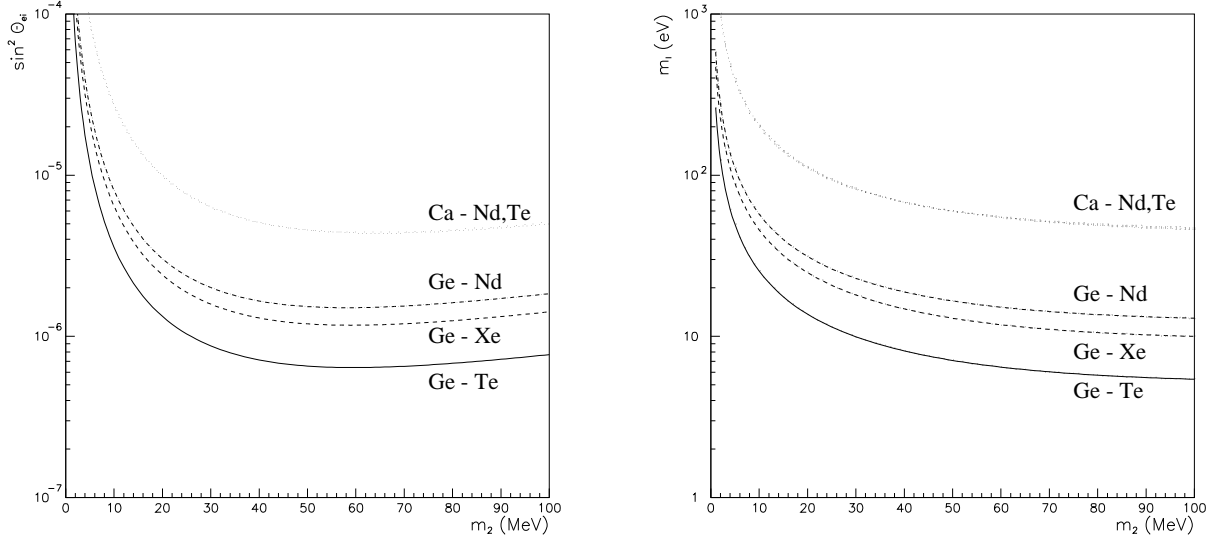

Figure 1: *left: Limit on the mixing angle $sin^2\theta_{ei}$ as a function of the heavy neutrino mass m_2 in the region of 1-100 MeV for five combinations of isotopes. At present the best limit is given by the Ge-Te pair. The combinations of the Ca-Nd and Ca-Te result are nearly identical. right: Upper limit of the Majorana mass of a light neutrino m_1 in the case of interference with one heavy neutrino. The Ge-Te pair results in the case of $m_2 \approx 100 MeV$ in a limit for m_1 of about 6 eV.*

Using eq.(11) and (15) it can be seen that $< m_{\nu_e} >$ gets an A-dependence because of $F(m_2, A)$ making it worthwile to look into experimental results of different double beta decay emitters. In Tab.1 a comparison of some double beta decay emitters as well as present limits on the half life $T_{1/2}^{0\nu}$ and the effective Majorana neutrinos $< m_{\nu_e} >$ are shown.

Isotope	^{48}Ca	^{76}Ge	^{100}Mo	^{128}Te	^{136}Xe	^{150}Nd
$T_{1/2}^{0\nu}$ present	9.5 E21	7.4 E24	4.4 E22	7.7E24	4E23	2.1E21
$< m_{\nu_e} >$	12.8	0.56	5.4	1.0	2.4	4.0
$T_{1/2}^{0\nu}$ future	1 E23	1.5 E25	1E25	7.7 E24	3.6 E25	1E23

Tab.1: Some selected isotopes with reasonable half life limits for double beta decay . Shown are the present limits for the half life $T_{1/2}^{0\nu}$, the resulting $< m_{\nu_e} >$- limit using the matrix elements from [13], as well as some proposed limits of ongoing, upcoming or planned experiments on $T_{1/2}^{0\nu}$.

3

Clearly there are two strategies to follow for looking at the A-dependence: The largest effect is expected if the two isotopes have the largest possible spread within A f.e. ^{48}Ca and ^{150}Nd or even ^{238}U. On the other hand much better experimental limits exist for the $0\nu\beta\beta$ decay half life for isotopes like ^{76}Ge and ^{128}Te . Fig.1a gives an idea of the variation in the mixing angle as a function of the heavy neutrino
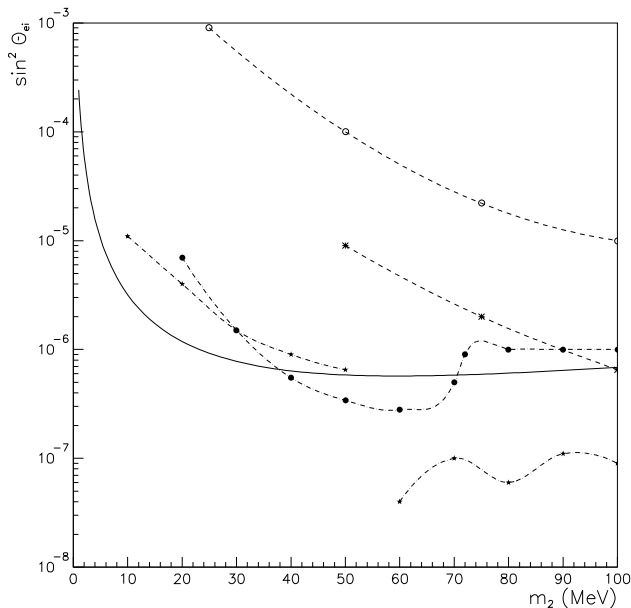

Figure 2: *Comparison of the Ge-Te double beta decay limit (solid line) on the mixing angle with other experiments. Shown are the results from [15] (open circles), [16] (asterix), [17] (stars) and [18] (filled circles). It can be seen that the double beta decay results give the best limit below about 35 MeV. The region above the curves are excluded.*

mass for five different pairs of isotopes. On the "small" A side it is ^{76}Ge (best half life limit) and ^{48}Ca (lowest A) on the "higher" side ^{128}Te (best half life limit) and ^{150}Nd (largest A with reasonable half life limit). It can be seen that the much better experimental half life limits of ^{76}Ge and ^{128}Te overcompensate the smaller separation in A. Therefore this pair will be used for a comparison with other experiments. Alternatively we can restrict the limit on the light neutrino mass m_1 assuming a nearly perfect cancellation of $< m_{\nu_e} >$ in ^{76}Ge by using a relation between two isotopes like [14]

$$m_1 < \frac{F(m_2, 76)}{\mid F(m_2, 76) - F(m_2, A) \mid}(< m_\nu(76) > + < m_\nu(A) >) \tag{16}$$

where A is one of the other isotopes. The value of the observable light neutrino mass as a function of the heavy one is shown in fig.1b. Using the simple mixing scheme of eq.(12) fig.2 shows the limits on the mixing parameter $\mid U_{ei} \mid^2 = sin^2\theta_{ei}$ because of the A-dependence in double beta decay in comparison with other experiments. It can be seen that in the region below about 35 MeV this limit is the most stringent
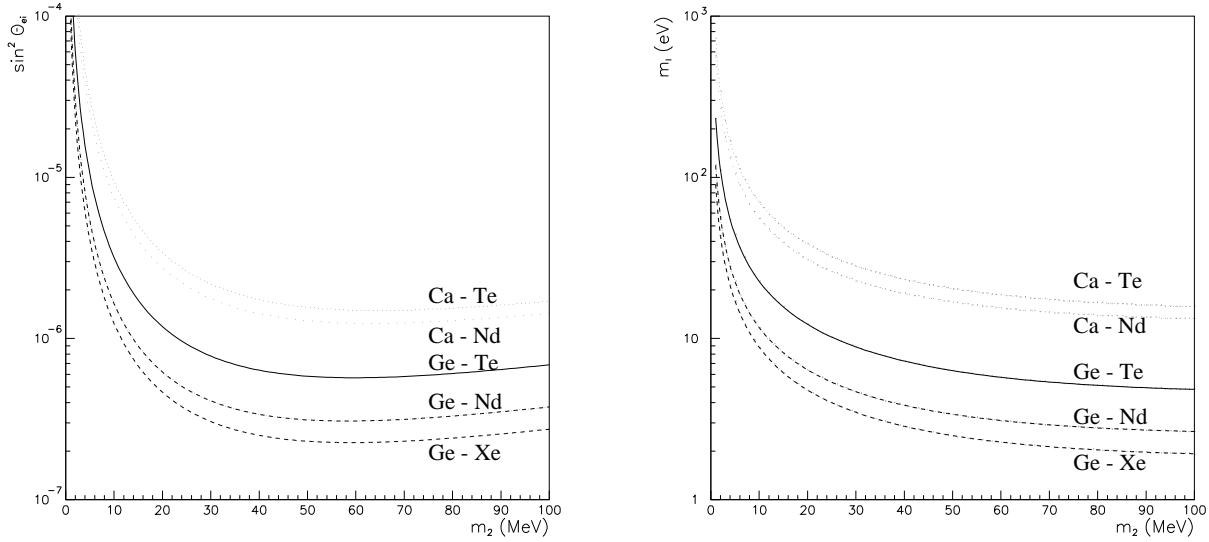
4

Figure 3: *Same presentations as fig.1 for ongoing, upcoming or planned experiments and their proposed half lifes limits. The best mixing angle limit (left) is now given by the Ge-Xe pair, which also gives an upper bound on m_1 of 2 eV assuming $m_2 \approx 100 MeV$.*

one. This can be improved by the ongoing,upcoming or planned future experiments. Using the proposed half live limits of the experiments shown in Tab.1 limits on the mass eigenstate and the mixing angle can be obtained as shown in fig.3. In this case the ^{76}Ge and ^{136}Xe data would dominate the bound, which is by a factor of about 3 lower than the present limits. So far all the considerations are based on very general arguments.

Now look at the standard model and assume that there are no extra neutrinos from yet unknown physics. The Z^o-resonance width results in 2.983 ± 0.025 [19] neutrinos flavours lighter than 45 GeV. Using the upper bounds on the different neutrino masses as given in eq. (1-3) it is obvious that m_2 can only be associated with ν_τ. Therefore the derived values for $\mid U_{ei} \mid^2$ correspond to $\mid U_{e\tau} \mid^2$ for $\Delta m^2 \approx 10^{12}$ eV^2. It should be mentioned that the bounds on $\mid U_{e\tau} \mid^2$ are weakened by some orders of magnitude by including ν_μ and assuming that there is a cancellation of the ν_μ and ν_τ contributions to $< m_{\nu_e} >$.

A direct consequence of the derived limit can be applied to the decay of $\nu_\tau \to \nu_e + e^+ e^-$ because of the lifetime dependence of $\tau \propto \mid U_{ei} \mid^2$ (neglecting other decay channels, see [5]). Different limits on the lifetime of ν_τ as a function of its mass including the one obtained via double beta decay can be seen in fig. 4. By using only rather model independent limits most of the allowed parameter space can be ruled out.

As a second example consider the possible evidence for neutrino oscillations as seen with the LSND-detector [21]. This would require a massive neutrino of ≈ 1 eV. Assume that the mass of the electron neutrino is somewhere in the region of 1-4 eV, which is still allowed by beta decay experiments, a heavy neutrino between 1-24 MeV, and that a perfect cancellation in ^{76}Ge $0\nu\beta\beta$ decay occurs. This would

5

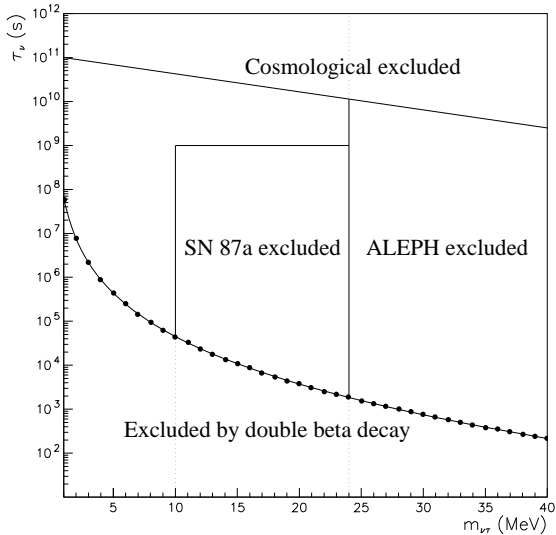Figure 4: *Lifetime of $\nu_\tau \to \nu_e + e^+ e^-$ against the tau-neutrino mass m_{ν_τ}. Shown is the exclusion due to double beta decay (lower curve) The vertical line at 24 MeV corresponds to the ALEPH-limit, the upper curve is excluded by cosmological arguments (Overdensity of the universe). These two bounds are valid for any decay mode. Also shown is the bound on the $\nu_\tau \to \nu_{e,\mu} + \gamma(e^+ e^-)$ decay-mode given by SN 1987a [20].*

imply values of $<m_{\nu_e}>$ in other isotopes like ^{100}Mo, ^{128}Te and ^{150}Nd in the range

$$2.7 \cdot 10^{-3} eV << m_{\nu_e} > < 0.25 eV \quad (^{100}Mo) \tag{17}$$

$$5.5 \cdot 10^{-3} eV << m_{\nu_e} > < 0.49 eV \quad (^{128}Te) \tag{18}$$

$$7.4 \cdot 10^{-3} eV << m_{\nu_e} > < 0.63 eV \quad (^{150}Nd) \tag{19}$$

The upper bounds are in the region of upcoming or planned experiments and such a scenario can be tested within the near future.

Conclusions

The effects of MeV Majorana neutrinos in double beta decay are investigated by comparing half life limits of different isotopes. Using only experimental bounds the most stringent limits on the mixing matrix element U_{ei} in the region from 1-35 MeV are obtained. Using the bound on U_{ei} a large part in the $\tau_{\nu_\tau} - m_{\nu_\tau}$ plane for the decay mode $\nu_\tau \to \nu_e e^+ e^-$ can be excluded. Whether there is a Majorana ν_e somewhere in the eV region and a MeV ν_τ can be tested or detected within the near future.

Acknowledgements

I would like to thank P. Bamert, C. P. Burgess and R. N. Mohapatra for helpful comments.

References

[1] K.Grotz,H.V.Klapdor, *The Weak Interaction in Nuclear-,Particle- and Astrophysics*, Adam Hilger, Bristol 1990, R.N. Mohapatra, B.P. Pal, *Massive Neutrinos in Physics and Astrophysics*, World Scientific, Singapore 1990, F. Boehm, P. Vogel, *Physics of massive neutrinos*, Cambridge Univ. Press, Cambridge 1992, B. Kayser, F. Gibrat-Debu, F. Perrier, *Physics of massive neutrinos*, World Scientific, Singapore 1989

[2] A.I.Belesev et al., *Phys. Lett.* B **350**, 263 (1995)

[3] K. Assamasgen et al., *Phys. Lett.* B **335**, 231 (1994)

[4] S. Buskulic et al., ALEPH-Col., *Phys. Lett.* B **349**, 585 (1995)

[5] G.Gyuk, M.S.Turner, *Nucl. Phys.* B (Proc. Suppl.) **38**, 13 (1995), R.N. Mohapatra, S.Nussinov, *Phys. Rev.* D **51**, 3843 (1995) A.D.Dolgov, S.Pastor, J.W.F.Valle, astro-ph 9506011

[6] N.Hata et al., *Phys. Rev. Lett.* **75**, 3977 (1995)

[7] G.C.Copi, D.N.Schramm, M.S.Turner, *ApJ* **455**, L95 (1995)

[8] P.Bamert, C.P.Burgess, R.N.Mohapatra, *Nucl. Phys.* B **438**, 3 (1995)

[9] A.Halprin, S.T.Petcov, S.P.Rosen, *Phys. Lett.* B **125**, 335 (1983)

[10] C.N.Leung, S.T.Petcov, *Phys. Lett.* B **145**, 416 (1984)

[11] H.V. Klapdor-Kleingrothaus, 2 ECT Workshop on double beta decay and related topics, Trento (Italy) eds. H.V. Klapdor-Kleingrothaus, S. Stoica, World Scientific 1996

[12] K. Muto, H.V. Klapdor, in Neutrinos, ed. H.V. Klapdor, Springer Verlag, Heidelberg 1988

[13] A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus, *Europhys. Lett.* **13**, 31 (1990)

[14] K. Grotz, H.V. Klapdor, *Nucl. Phys.* A **460**, 395 (1986)

[15] S.Baranov et al., *Phys. Lett.* B **302**, 336 (1993)

[16] G.Bernadi et al., *Phys. Lett.* B **166**, 479 (1986)

[17] D.I.Britton et al., *Phys. Rev.* D **46**, R885 (1992)

[18] N.DeLeener-Rosier et al., *Phys. Rev.* D **43**, 3611 (1991)

[19] Review of Particle Properties, Particle Data Group (1994)

[20] R.N.Mohapatra, S.Nussinov, X.Zhang, *Phys. Rev.* D **49**, 3434 (1994)

[21] C. Athanassopoulos et al., LSND-Col., *Phys. Rev. Lett.* **75**, 2650 (1995), nucl-ex 9605001