FIRST EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY – AND WORLD STATUS OF DOUBLE BETA EXPERIMENTS

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ABSTRACT

Nuclear double beta decay provides an extraordinarily broad potential to search for beyond-standard-model physics. The occurrence of the neutrinoless decay \(0\nu\beta\beta\) mode has fundamental consequences: first total lepton number is not conserved, and second, the neutrino is a Majorana particle. Further the effective mass measured allows to put an absolute scale of the neutrino mass spectrum. In addition, double beta experiments yield sharp restrictions also for other beyond standard model physics. These include SUSY models (R-parity breaking and conserving), leptoquarks (leptoquark-Higgs coupling), compositeness, left-right symmetric models (right-handed W boson mass), test of special relativity and of the equivalence principle in the neutrino sector and others. First evidence for neutrinoless double beta decay was given in 2001, by the HEIDELBERG-MOSCOW experiment. The HEIDELBERG-MOSCOW experiment is the by far most sensitive \(0\nu\beta\beta\) experiment since more than 10 years. It is operating 11 kg of enriched \(^{76}\text{Ge}\) in the GRAN SASSO Underground Laboratory. The analysis of the data taken from 2 August 1990 - 20 May 2003, is presented here. The collected statistics is 71.7 kg y. The background achieved in the energy region of the Q value for double beta decay is 0.11 events/kg y keV. The two-neutrino accompanied half-life is determined on the basis of more than 100 000 events to be \((1.74^{+0.18}_{-0.16}) \times 10^{21}\) years. The confidence level for the neutrinoless signal is \(4.2\) σ level (more than \(5\) σ in the pulse-shape-selected spectrum). The half-life is \(T^{1/2}_{\text{\nu}} = (1.19^{+0.37}_{-0.23}) \times 10^{25}\) years. The effective neutrino mass deduced is \((0.2 - 0.6)\) eV (99.73% c.l.), with the consequence that neutrinos have degenerate masses, and consequently still considerably, and contribute to hot dark matter in the Universe. The sharp boundaries for other beyond SM physics, mentioned above, are comfortably competitive to corresponding results from high-energy accelerators like TEVATRON, HERA, etc. Some discussion is given on future \(\beta\beta\) experiments.

1. Introduction

Since 40 years huge experimental efforts have gone into the investigation of nuclear double beta decay which probably is the most sensitive way to look for (total) lepton number violation and probably the only way to decide the Dirac or Majorana nature of the neutrino. It has further perspectives to probe also other types of beyond standard model physics. This thorny way has been documented recently in some detail \[29,39,31\].
With respect to half-lives to explore lying, with the order of $10^{25}$ years, in a range on 'half way' to that of proton decay, the two main experimental problems were to achieve a sufficient amount of double beta emitter material (source strength) and to reduce the background in such experiment to an extremely low level. In both directions large progress has been made over the decades. While the first experiment using source as detector [35], had only grams of material to its disposal (10.6 g of CaF$_2$), in the last years up to more than 10 kg of enriched emitter material have been used. Simultaneously the background of the experiments has been reduced strongly over the last 40 years. For example, compared to the first Germanium $\beta\beta$ experiment [45], working still with natural Germanium, containing the double beta emitter $^{76}$Ge only with 7.8%, 40 years later the background in the HEIDELBERG-MOSCOW experiment is reduced by a factor of $10^4$.

The final dream behind all these efforts was less to see a standard-model allowed second-order effect of the weak interaction in the nucleus - the two-neutrino-accompanied decay mode - which has been observed meanwhile for about 10 nuclei - (see e.g. [29]) but to observe neutrinoless double beta decay, and with this a first hint of beyond standard model physics, yielding at the same time a solution of the absolute scale of the neutrino mass spectrum.

2. Performance of the Experiment and Data Taking

2.1. General

The HEIDELBERG-MOSCOW experiment, proposed already in 1987 [31], has been looking for double beta decay of $^{76}$Ge since August 1990 until November 30, 2003 in the Gran Sasso Underground Laboratory. It was using the largest source strength of all double beta experiments at present, and has reached a record low level of background, not only for Germanium double beta decay search. It has demonstrated this during more than a decade of measurements and is since more then ten years the most sensitive double beta decay experiment worldwide. The experiment was since 2001 operated only by the Heidelberg group, which also performed the analysis of the experiment from its very beginning.

The experiment has been carried out with five high-purity p-type detectors of Ge enriched to 86% in the isotope $^{76}$Ge (in total 10.96 kg of active volume). These were the first enriched high-purity Ge detectors ever produced. So, the experiment starts from the cleanest thinkable source of double beta emitter material, which at the same time is used as detector of $\beta\beta$ events.

A description of the experimental details has been given in [1,2,3,10]. This will not be repeated in this paper, instead we concentrate on the results and their consequences. But let us just mention some of the most important features of the experi-
1. Since the sensitivity for the $0\nu\beta\beta$ half-life is $T_{1/2}^{0\nu} \sim a \times \epsilon \sqrt{\frac{M}{\Delta E B}}$ (and $\frac{1}{\sqrt{T_{1/2}^{0\nu}}} \sim \langle m_\nu \rangle$), with $a$ denoting the degree of enrichment, $\epsilon$ the efficiency of the detector for detection of a double beta event, $M$ the detector (source) mass, $\Delta E$ the energy resolution, $B$ the background and $t$ the measuring time, the sensitivity of our 11 kg of enriched $^{76}$Ge experiment corresponds to that of an at least 1.2 ton natural Ge experiment. After enrichment - the other most important parameters of a $\beta\beta$ experiment are: energy resolution, background and source strength.

2. The high energy resolution of the Ge detectors of 0.2% or better, assures that there is no background for a $0\nu\beta\beta$ line from the two-neutrino double beta decay in this experiment, in contrast to most other present experimental approaches, where limited energy resolution is a severe drawback.

3. The efficiency of Ge detectors for detection of $0\nu\beta\beta$ decay events is close to 100% (95%, see 2).

4. The source strength in this experiment of 11 kg is the largest source strength ever operated in a double beta decay experiment.

5. The background reached in this experiment, is $0.113 \pm 0.007$ events /kg y keV (in the period 1995-2003) in the $0\nu\beta\beta$ decay region (around $Q_{\beta\beta}$). This is the lowest limit ever obtained in such type of experiment.

6. The statistics collected in this experiment during 13 years of stable running is the largest ever collected in a double beta decay experiment. The experiment took data during $\sim 80\%$ of its installation time.

7. The Q value for neutrinoless double beta decay has been determined recently with high precision 33.

3. Data and Analysis

Figs.1,2 show the total sum spectrum measured over the full energy range of all five detectors for the period November 1995 to May 2003. The identified lines are indicated with their source of origin (for details see 18).

Figs.3,4 show the part of the spectrum around $Q_{\beta\beta}$, in the range 2000 - 2060 keV, measured in the period August 1990 to May 2003 and November 1995 to May 2003. Non-integer numbers in the sum spectra are simply a binning effect.

3.1. Energy Calibration

Precise energy calibration for all detectors before summing the individual 2142 runs taken with the detectors, and finally summing the sum spectra of the different detectors (in total summing 9 570 data sets) is decisive to achieve a good energy resolution of the total spectrum, and an optimum sensitivity of the experiment. For details see 2. A list of the energies of the identified lines (Figs.12) is given in a
Figure 1: The total sum spectrum measured over the full energy range (low-energy part) of all five detectors (in total 10.96 kg enriched in $^{76}$Ge to 86%) - for the period November 1995 to May 2003.

recent paper 18, here we concentrate on the range of interest around $Q_{\beta\beta}$.

3.2. Analysis of the Spectra

In the measured spectra (Figs.3 ÷ 4) we see in the range around $Q_{\beta\beta}$ the $^{214}$Bi lines at 2010.7, 2016.7, 2021.8, 2052.9 keV, the line at $Q_{\beta\beta}$ and a candidate of a line at $\sim$ 2030 keV (see also 13, 19)\(^a\) The spectra have been analyzed by different methods: Least Squares Method, Maximum Likelihood Method (MLM) and Feldman-Cousins Method. The analysis is performed without subtraction of any background. We always

\(^a\)The objections raised after our first paper 4 concerning these lines and other points, by Aalseth et al. (Mod.Phys.Lett.A17:1475-1478,2002 and hep-ex/0202018 v.1), have been shown to be wrong already in 7 and in 13, and later in 15 and 19. So this 'criticism' was already history, before we reached the higher statistics presented in this paper.
process background-plus-signal data since the difference between two Poissonian variables does not produce a Poissonian distribution. This point has to be stressed, since it is sometimes overlooked. So, e.g., in a formula is developed making use of such subtraction and as a consequence the analysis given in provides overestimated standard errors.

The large improvement of the present analysis (for details see) compared to our paper from 2001, is clearly seen from Fig. showing the new analysis of the data 1990-2000, as performed here – to be compared to the corresponding figure in. One reason lies in the stricter conditions for accepting data into the analysis. The spectrum in Fig. now corresponds to 50.57 kg y to be compared to 54.98 kg y in, for the same measuring period. The second reason is a better energy calibration of the individual runs. The third reason is the refined summing procedure
Figure 3: The total sum spectrum of all five detectors (in total 10.96 kg enriched in $^{76}$Ge), for the period: left: November 1990 to May 2003 (71.7 kg y) in the range 2000 - 2060 keV. right: November 1995 to May 2003 (56.66 kg y) in the range 2000 - 2060 keV and its fit (see section 3.2).

Figure 4: The total sum spectrum of all five detectors (in total 10.96 kg enriched in $^{76}$Ge), in the range (2000 - 2060) keV and its fit, for the period August 1990 to May 2000 (50.57 kg y).

of the individual data sets mentioned above and the correspondingly better energy resolution of the final spectrum. (For more details see [1][2][3]). The signal strength seen in the individual detectors in the period 1990-2003 is shown in [3].

We tested the confidence intervals calculated by the fitting programs with numerical simulations (see [1][2][3]). As done earlier for other statistical methods [1][2][3][4], we have simulated 100,000 spectra with Poisson-distributed background and a Gaussian-shaped (Poisson-distributed) line of given intensity, and have investigated, in how many cases we find in the analysis the known intensities inside the given confidence range. The result shows that the confidence levels determined are correct within small
errors (for details see 23).}

4. Results

4.1. Full Spectra

Figs. 3-4 show together with the measured spectra in the range around $Q_{\beta\beta}$ (2000 - 2060 keV), the fit by the least-squares method. A linear decreasing shape of the background as function of energy was chosen corresponding to the complete simulation of the background performed in 18 by GEANT4 (see Fig. 5).

Figure 5: Monte Carlo simulation of the background in the range of $Q_{\beta\beta}$ by GEANT4, including all known sources of background in the detectors and the setup. This simulation 18 seems to be the by far most extensive and complete one ever made for any double beta experiment. The background around $Q_{\beta\beta}$ is expected to be flat, the only lines visible should be some weak $^{214}$Bi lines (from 18).

In the fits in Figs. 3-4 the peak positions, widths and intensities are determined simultaneously, and also the *absolute* level of the background.

The signal at $Q_{\beta\beta}$ in the full spectrum at $\sim 2039$ keV reaches a 4.2 $\sigma$ confidence level for the period 1990-2003 (28.8 ± 6.9) events, and of 4.1 $\sigma$ for the period 1995-2003 (23.0 ± 5.7) events. The results of the new analysis are consistent with the results given in 1456. The intensities of all other lines are given in 23.

We have given a detailed comparison of the spectrum measured in this experiment with other Ge experiments in 19. It is found that the most sensitive experiment with natural Ge detectors 14, and the first experiment using enriched (not yet high-purity) $^{76}Ge$ detectors 15 find essentially the same background lines ($^{214}Bi$ etc.), but *no* indication for the line near $Q_{\beta\beta}$. This is consistent with the rates expected from the present experiment due to their lower sensitivity: $\sim 0.7$ and $\sim 1.1$ events,
respectively. It is also consistent with the result of the IGEX $^{76}\text{Ge}$ experiment \(^{16}\), which collected only a statistics of 8.8 kgy, before finishing in 1999, and which should expect $\sim 2.6$ events, which they might have missed. Their published half-life limit is overestimated as result of an arithmetic mistake (see \(^{17}\)).

Figure 6: Top, upper part: The pulse-shape selected spectrum of single site events measured with detectors 2,3,4,5 from 1995-2003, see text. Top, lower part: The full spectrum measured with detectors 2,3,4,5 from 1995-2003. Bottom: As in top figure, upper part, but energy range 2000-2100 keV.

4.2. Time Structure of Events

There are at present no other running experiments (with reasonable energy resolution) which can - not to speak about their lower sensitivity - in principle give any further-going information in the search for double beta decay than shown up to this point: namely a line at the correct energy $Q_{\beta\beta}$. Also most future projects cannot
determine more. The HEIDELBERG-MOSCOW experiment developed some additional tool of independent verification. The method is to exploit the time structure of the events and to select $\beta\beta$ events by their pulse shape. The result is shown in Fig. 6.

![Figure 7: The pulse-shape selected spectrum measured with detectors 2,3,4,5 from 1995÷2003 in the energy range of (100÷3000) keV, see text.](image)

Here a subclass of shapes selected by the neuronal net method used earlier is shown. Except a line which sticks out sharply near $Q_{\beta\beta}$, all other lines are very strongly suppressed. Fig. 6 also shows the full spectrum in this range. **When taking the range 2000-2100 keV and conservatively assuming all structures except the line at $Q_{\beta\beta}$ to be part of a constant background, a corresponding fit yields a signal at $Q_{\beta\beta}$ of more than 5$\sigma$ (see fig. 6).** The method seems also to fulfill the criterion to select properly the continuous $2\nu\beta\beta$ spectrum (see Fig. 7).

The energy of this line determined by the spectroscopy ADC is slightly below $Q_{\beta\beta}$, but still within the statistical variation for a weak line (see 19). This can be understood as result of ballistic effects (for details see 26). The 2039 keV line as a single site events signal cannot be the double escape line of a $\gamma$-line whose full energy peak would be expected at 3061 keV, since no indication of a line is found there in the spectrum measured up to 8 MeV (see 23).

5. Half-Life of Neutrinoless Double Beta Decay of $^{76}Ge$

We have shown in chapter 4 that the signal found at $Q_{\beta\beta}$ is consisting of single site events and is not a $\gamma$ line. The signal does not occur in the Ge experiments not enriched in the double beta emitter $^{76}Ge$ 14, 12, 19, while neighbouring background lines appear consistently in these experiments.
Table 1: Half-life for the neutrinoless decay mode and deduced effective neutrino mass from the HEIDELBERG-MOSCOW experiment (the nuclear matrix element of $^{23}$ is used). Shown are in addition to various accumulated total measuring times also the results for four non-overlapping data sets: the time periods 11.1995-09.1999 and 09.1999÷05.2003 for all detectors, and the time period 1995÷2003 for two sets of detectors: 1+2+4, and 3+5. *) denotes best value.

| Significance $[kg \cdot y]$ | Detectors | $T_{1/2}^{\nu}$ $[y]$ $(3\sigma$ range) | $\langle m \rangle$ [eV] $(3\sigma$ range) | Conf. level $(\sigma)$ |
|----------------------------|-----------|----------------------------------------|----------------------------------------|------------------|
| **Period 8.1990 ÷ 5.2003** |
| 71.7 | 1,2,3,4,5 | $(0.69 - 4.18) \times 10^{25}$ | $(0.24 - 0.58)$ | 4.2 |
| | | $1.19 \times 10^{25}$* | | |
| **Period 11.1995 ÷ 5.2003** |
| 56.66 | 1,2,3,4,5 | $(0.67 - 4.45) \times 10^{25}$ | $(0.23 - 0.59)$ | 4.1 |
| | | $1.17 \times 10^{25}$* | $0.45^*$ | |
| 51.39 | 2,3,4,5 | $(0.68 - 7.3) \times 10^{25}$ | $(0.18 - 0.58)$ | 3.6 |
| | | $1.25 \times 10^{25}$* | $0.43^*$ | |
| 42.69 | 2,3,5 | $(0.88 - 4.84) \times 10^{25}$ $(2\sigma$ range) | $(0.22 - 0.51)$ $(2\sigma$ range) | 2.9 |
| | | $1.5 \times 10^{25}$* | $0.39^*$ | |
| 28.27 | 1,2,4 | $(0.67 - 6.56) \times 10^{25}$ $(2\sigma$ range) | $(0.19 - 0.59)$ $(2\sigma$ range) | 2.5 |
| | | $1.22 \times 10^{25}$* | $0.44^*$ | |
| 28.39 | 3,5 | $(0.59 - 4.29) \times 10^{25}$ $(2\sigma$ range) | $(0.23 - 0.63)$ $(2\sigma$ range) | 2.6 |
| | | $1.03 \times 10^{25}$* | $0.48^*$ | |
| **Period 11.1995 ÷ 09.1999** |
| 26.59 | 1,2,3,4,5 | $(0.43 - 12.28) \times 10^{25}$ | $(0.14 - 0.73)$ | 3.2 |
| | | $0.84 \times 10^{25}$* | $0.53^*$ | |
| **Period 09.1999 ÷ 05.2003** |
| 30.0 | 1,2,3,4,5 | $(0.60 - 8.4) \times 10^{25}$ | $(0.17 - 0.63)$ | 3.5 |
| | | $1.12 \times 10^{25}$* | $0.46^*$ | |
On this basis we translate the observed numbers of events into half-lives for neutrinoless double beta decay. In Table 1 we give the half-lives deduced from the full data sets taken in the years 1995-2003 and in 1990-2003 and of some partial data sets. In all cases the signal is seen consistently. Also given are the deduced effective neutrino masses.

The result obtained is consistent with the limits given earlier, and with the results given in 4, 5, 6. Concluding we confirm, with 4.2σ (99.973% c.l.) probability (more than 5σ in the pulse-shape selected spectrum), our claim from 2001 of first evidence for the neutrinoless double beta decay mode.

6. Consequences for Particle Physics, Neutrino Physics and Other Beyond Standard Model Physics

Lepton number violation: The most important consequence of the observation of neutrinoless double beta decay is, that lepton number is not conserved. This is fundamental for particle physics.

Majorana nature of neutrino: Another fundamental consequence is that the neutrino is a Majorana particle (see, e.g. 41, 42, but also 43). Both of these conclusions are independent of any discussion of nuclear matrix elements.

Effective neutrino mass: The matrix element enters when we derive a value for the effective neutrino mass - making the most natural assumption that the 0νββ decay amplitude is dominated by exchange of a massive Majorana neutrino. The half-life for the neutrinoless decay mode is under this assumption given by

$$[T_{1/2}^{0\nu}(0_{i}^{+} \rightarrow 0_{f}^{+})]^{-1} = C_{mm} \langle \frac{m}{m} \rangle^{2} + C_{\eta\eta} \langle \eta \rangle^{2} + C_{\lambda\lambda} \langle \lambda \rangle^{2} + C_{m\eta} \langle \frac{m}{m} \rangle \langle \eta \rangle + C_{m\lambda} \langle \frac{m}{m} \rangle \langle \lambda \rangle + C_{\eta\lambda} \langle \eta \rangle \langle \lambda \rangle,$$

where $m^{(i)}_{ee} \equiv |m^{(i)}_{ee}| \exp(i\phi_{i})$ (i = 1, 2, 3) are the contributions to the effective mass ($\langle m \rangle$) from individual mass eigenstates, with $\phi_{i}$ denoting relative Majorana phases connected with CP violation, and $C_{mm}, C_{\eta\eta}, \ldots$ denote nuclear matrix elements squared, which can be calculated, (see, e.g. 29, 33, 37, for a review). Ignoring contributions from right-handed weak currents, on the right-hand side of eq.(1) only the first term remains.

Using the nuclear matrix element from 24, 25, we conclude from the half-life given above the effective mass ($\langle m \rangle$) to be ($\langle m \rangle = (0.2 \div 0.6) \text{ eV}$ (99.73% c.l.), with best value of $\sim 0.4 \text{ eV}$.

The matrix element given by 23 was the prediction closest to the later measured 2νββ decay half-life of $(1.74^{+0.18}_{-0.16}) \times 10^{25}$ years. It underestimates the 2ν matrix
elements by 32% and thus these calculations will also underestimate (to a smaller extent) the matrix element for $0\nu\beta\beta$ decay, and consequently correspondingly overestimate the (effective) neutrino mass. The value for the effective mass thus in reality will be somewhat lower, than deduced above, down to $\sim 0.3$ eV. Allowing conservatively for an uncertainty of the nuclear matrix element of $\pm 50\%$ the range for the effective mass may widen to $\langle m \rangle = (0.1 - 0.9)$ eV (99.73% c.l.).

Neutrinos degenerate in mass: With the value deduced for the effective neutrino mass $\langle m \rangle = 0.4$ eV, 3$\sigma$ confidence range $(0.1 - 0.9)$ eV - allowing already for an uncertainty of the nuclear matrix element of a factor of $\pm 50\%$) on possible neutrino mass schemes. The bars denote allowed ranges of $\langle m \rangle$ in different neutrino mass scenarios, still allowed by neutrino oscillation experiments (see [28, 52]). All models except the degenerate one are excluded by the new $0\nu\beta\beta$ decay result. Also shown is the exclusion line from WMAP, plotted for $\sum m_\nu < 1.0$ eV [56] (which is according to [73] too strict). WMAP does not rule out any of the neutrino mass schemes. Further shown are the expected sensitivities for the future potential double beta experiments CUORE, MOON, EXO and the 1 ton and 10 ton project of GENIUS [29, 31, 63] (from [52]).

Neutrinos as hot dark matter: The effective neutrino mass determined by $0\nu\beta\beta$ decay allows a considerable fraction of hot dark matter in the Universe carried
by neutrinos.

Other beyond Standard Model Physics: Assuming other mechanisms to dominate the $0\nu\beta\beta$ decay amplitude, which have been studied extensively in our group, and other groups, in recent years, the result allows to set stringent limits on parameters of SUSY models, leptoquarks, compositeness, masses of heavy neutrinos, the right-handed $W$ boson and possible violation of Lorentz invariance and equivalence principle in the neutrino sector. Figs.9,10,11 show as examples some of the relevant graphs which can in principle contribute to the $0\nu\beta\beta$ amplitude and from which bounds on the corresponding parameters can be deduced assuming conservatively the measured half-life as upper limit for the individual processes.

Figure 9: Examples of Feynman graphs for $0\nu\beta\beta$ decay within R–parity violating supersymmetric models.

Figure 10: Examples of $R_P$ conserving SUSY contributions to $0\nu\beta\beta$ decay.

Figs.12-14 show some results. The most strict limit for the R-parity - breaking Yukawa coupling $\lambda'_{111}$ in R-violating SUSY models is coming from $0\nu\beta\beta$-decay. It is much stricter then the limits obtained by accelerators, whose limitation in energy is visible in Fig. 12 (from [31]).
Figure 11: Examples of Feynman graphs for $0\nu\beta\beta$ decay within LQ models. $S$ and $V^\mu$ stand for scalar and vector LQs, respectively

$$d \xrightarrow{\nu} e$$
$$d \xrightarrow{\nu^\prime} e$$

Figure 12: Comparison of sensitivities of existing and future experiments on R$_p$-violating SUSY models in the plane $\lambda'_{111}$-$m_{\tilde{q}}$. Note the double logarithmic scale! Shown are the areas currently excluded by the experiments at the TEVATRON and HERA-B, the limit from charged-current universality, denoted by CCU, and the limit from $0\nu\beta\beta$-decay from the HEIDELBERG-MOSCOW Experiment. The area beyond (or left of) the lines is excluded. The estimated sensitivity of LHC is also given (from [31]).
Figure 13: Discovery limit for $e^-e^- \rightarrow W^-W^-$ at a linear collider as function of the mass $M_i$ of a heavy left-handed neutrino, and of $U_{ei}^2$ for $\sqrt{s}$ between 500 GeV and 10 TeV. In all cases the parameter space above the line corresponds to observable events. The limits from the HEIDELBERG-MOSCOW $0\nu\beta\beta$ experiment are shown also, the areas above the $0\nu\beta\beta$ contour line are excluded. The horizontal line denotes the limit on neutrino mixing, $U_{ei}^2$, from LEP (from 68).

The lower limit for super-heavy left-handed neutrino from the $0\nu\beta\beta$ HEIDELBERG-MOSCOW experiment corresponds to the discovery potential for the inverse process $e^-e^- \rightarrow W^-W^-$ of a linear collider of 1-2 TeV (see Fig.13). The constraints concerning composite excited neutrinos of mass $M-N$ obtained from $0\nu\beta\beta$ decay (HEIDELBERG-MOSCOW experiment) are more strict than the results of LEPII, as shown in Fig.14. For a further discussion and for references we refer to 29,30,31,32.

7. Conclusion - Perspectives

Recent information from many independent sides seems to condense now to a nonvanishing neutrino mass of the order of the value found by the HEIDELBERG-MOSCOW experiment. This is the case for the results from CMB, LSS, neutrino oscillations, particle theory and cosmology (for a detailed discussion see 1,2,3). To mention a few examples: Neutrino oscillations require in the case of degenerate neutrinos common mass eigenvalues of $m > 0.04$ eV. An analysis of CMB, large scale structure and X-ray from clusters of galaxies yields a 'preferred' value for $\sum m_\nu$ of $0.6$ eV 31. WMAP yields $\sum m_\nu < 1.0$ eV 32, SDSS yields $\sum m_\nu < 1.7$ eV 33. Theoretical papers require degenerate neutrinos with $m > 0.1$, or $0.2$ eV or $0.3$ eV 34, and the recent alternative cosmological concordance model requires relic neutrinos.
with mass of order of eV\cite{60}. As mentioned already earlier\cite{102}, the results of double beta decay and CMB measurements together indicate that the neutrino mass eigenvalues have the same CP parity, as required by the model of\cite{19}. Also the approach of\cite{73} comes to the conclusion of a Majorana neutrino. The Z-burst scenario for ultra-high energy cosmic rays requires $m_\nu \sim 0.4 \text{ eV}$\cite{50,51}, and also a non-standard model (g-2) has been connected with degenerate neutrino masses $>0.2 \text{ eV}$\cite{46}. The neutrino mass determined from $0\nu\beta\beta$ decay is consistent also with present models of leptogenesis in the early Universe\cite{66}. It has been discussed that the Majorana nature of the neutrino tells us that spacetime does realize a construct that is central to construction of supersymmetric theories\cite{36}.

**Future:** With the HEIDELBERG-MOSCOW experiment, the era of small smart experiments is over. Fig. 15 shows the present result and a comparison to the potential of the most sensitive other double beta decay experiments and the possible potential of some future projects. It is visible that the presently running experiments have hardly a chance, to reach the sensitivity of the HEIDELBERG-MOSCOW experiment. New approaches and considerably enlarged experiments would be required to fix the $0\nu\beta\beta$ half life with higher accuracy. This will, however, only marginally improve the precision of the deduced neutrino mass, because of the uncertainties in the nuclear matrix elements, which probably hardly can be reduced to less than 50%.

One has to keep in mind further, that no more can be learnt on other beyond
standard model physics parameters from future more sensitive experiments. The reason is that there is a half-life now, and no more a limit on the half-life, which could be further reduced.

From future projects one has to require that they should be able to differentiate between a $\beta$ and a $\gamma$ signal, or that the tracks of the emitted electrons should be measured. At the same time, as is visible from the present information, the energy resolution should be at least in the order of that of Ge semiconductor detectors, or better. These requirements exclude at present calorimeter experiments like CUORE, CUORICINO, which cannot differentiate between a $\beta$ and $\gamma$ signal, etc, but also experiments like EXO [72], if the latter will not be able to reconstruct the tracks of the electrons, as it seems at present.

The most discussed ’short-term’ ”confirmation experiments” at present are CUORICINO/CUORE and NEMO. Let us therefore, to avoid usual misunderstandings, give a few comments.

**CUORICINO, CUORE:**

The general background problems of CUORICINO are illustrated by the fact, that this experiment until now is not able to see the $2\nu\beta\beta$ decay of $^{130}Te$, whose half life is...
experimentally known to be \( T_{1/2}^{0\nu} = (2.7\pm 0.1) \times 10^{21} \) years \(^{69}\), i.e. similar to the \( 2\nu\beta\beta \) half-life of \(^{76}Ge\), which is very clearly seen in the HEIDELBERG-MOSCOW experiment (see, e.g. \(^{18}\)). The background in the range of \( Q_{\beta\beta} \) is for CUORICINO at present \(^{70}\) a factor of two higher than in the HEIDELBERG-MOSCOW experiment.

The present half-life limit for \( 0\nu\beta\beta \) decay given as \( 1.8 \times 10^{24} \) years on a 90% c.l. (statistical method is not described, could however be important, see e.g. \(^{17}\)), after a measuring time of 10.8 kgy. The half-life corresponding to the effective neutrino mass deduced from the HEIDELBERG-MOSCOW experiment, for the case of \(^{130}Te\) is according to \(^{24}\) \( T_{1/2}^{0\nu} = 2.5 \times 10^{24} \) y. At a 90% c.l. a corresponding limit could be reached by CUORINO in additional 5 months of continuous running, i.e. realistically in more than a year. Allowing an uncertainty in the calculated matrix element of a factor of 2, however, could require a 16 times larger measuring time, i.e. \( \sim 30 \) years, to make a statement on a 90% confidence level. This means that the CUORICINO experiment can, with good luck, confirm the Heidelberg-Moscow result (on a reasonable not only 90% c.l.) in several years, but it can never disprove it.

The full version CUORE with about a factor of 15 larger detector mass than CUORICINO could, with background of CUORICINO, have a sensitivity to probe the HEIDELBERG-MOSCOW result in about one year of continuous measuring on a 90% confidence level. So unfortunately also this experiment would require many years of measurement to make a statement on a reasonable confidence level.

**NEMO:**

The NEMO project can see tracks, but unfortunately has at present only a small efficiency (14%) \(^{71}\), and a low energy resolution of more than 200 keV not to talk about the background problems from Rn.

Therefore limits given for \( 0\nu\beta\beta \) decay are lying at present \(^{71}\) only at \( T_{1/2}^{0\nu} = 1.9 \times 10^{23} \) y \((^{82}Se)\) and \( T_{1/2}^{0\nu} = 3.5 \times 10^{23} \) y \((^{100}Mo)\) on a 90% c.l, i.e. on a 1.5 sigma level, for 0.55 and 5 kg y of measurement, respectively. To improve these limits by a factor of 20, which is required (see \(^{24}\) ) at least, to check the results of the HEIDELBERG-MOSCOW experiment presented in this paper, the measurement times have to be increased by a factor of 400. This means that this experiment is not able to check the HEIDELBERG-MOSCOW result.

**GENIUS:**

An in principle much more sensitive project is probably the GENIUS project, proposed already in 1997 \(^{61}\) \(^{67}\) \(^{68}\) \(^{62}\) \(^{63}\) \(^{30}\) \(^{29}\), A GENIUS Test Facility, (which could already be used to search for cold dark matter by the annual modulation effect) has started operation with 10 kg of natural Germanium detectors in liquid nitrogen in Gran-Sasso on May 5, 2003 \(^{23}\) \(^{21}\) \(^{20}\) \(^{22}\), increased to 15 kg in October 2005. The results from the GENIUS-Test-Facility
show however, that though the search for cold dark matter should be feasible, it may be technically rather difficult, to increase the sensitivity of a GENIUS-like experiment for neutrinoless double beta decay beyond that of the HEIDELBERG-MOSCOW experiment.

However, if one wants to get independent evidence for the neutrinoless double beta decay mode, one would probably wish to see the effect in another isotope, which would then simultaneously give additional information also on the nuclear matrix elements. In view of these considerations, future efforts to obtain deeper information on the process of neutrinoless double beta decay, would require a new experimental approach, different from all, what is at present pursued.

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