

Heidelberg - Moscow Experiment on Neutrinoless Double Beta Decay

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Abstract

The HEIDELBERG-MOSCOW experiment, which is the most sensitive double beta decay experiment since ten years has been regularly continued until end of November 2003. An analysis of the data has been performed already until May 20, 2003. The experiment yields now, on a 4σ level, evidence for lepton number violation and proves that the neutrino is a Majorana particle. It further shows that neutrino masses are degenerate. In addition it puts several stringent constraints on other physics beyond the Standard Model. Among others it opens the door to test various supersymmetric theory scenarios, for example it gives the sharpest limit on the parameter λ'_{111} in the R-parity violating part of the superpotential, and gives information on the splitting of the sneutrino-antisneutrino system. The result from the HEIDELBERG-MOSCOW experiment is consistent with recent results from CMB investigations, with high energy cosmic rays, with the result from the g-2 experiment and with recent theoretical work. It is indirectly supported by the analysis of other Ge double beta experiments. Recent criticism of various kind has been shown to be wrong, among others by measurements performed in 2003 with a ^{214}Bi source (^{226}Ra), by simulation of the background in the range of $Q_{\beta\beta}$ by GEANT4, and by deeper investigation of statistical features such as sensitivity of peak search, and relevance of width of window of analysis.

1 Introduction

Double beta decay is the most sensitive probe to test lepton number conservation. Further it seems to be the only way to decide about the Dirac or Majorana nature of the neutrino.

Double beta decay can contribute decisively to the field of neutrino physics also by setting an absolute scale to neutrino masses, which cannot be observed from neutrino oscillation experiments.

The observable of double beta decay is the effective neutrino mass

$$\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2} |m_{ee}^{(2)}| + e^{i\phi_3} |m_{ee}^{(3)}|,$$

with U_{ei} denoting elements of the neutrino mixing matrix, m_i neutrino mass eigenstates, and ϕ_i relative Majorana CP phases. It can be written in terms of oscillation parameters [14]

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1, \quad (1)$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2}, \quad (2)$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}. \quad (3)$$

The effective mass $\langle m \rangle$ is related with the half-life for $0\nu\beta\beta$ decay via $(T_{1/2}^{0\nu})^{-1} \sim \langle m_\nu \rangle^2$, and for the limit on $T_{1/2}^{0\nu}$ deducible in an experiment we have

$$T_{1/2}^{0\nu} \sim \epsilon \times a \sqrt{\frac{Mt}{\Delta EB}}, \quad (4)$$

Here a is the isotopical abundance of the $\beta\beta$ emitter; M is the active detector mass; t is the measuring time; ΔE is the energy resolution; B is the background count rate and ϵ is the efficiency for detecting a $\beta\beta$ signal. Determination of the effective mass fixes the absolute scale of the neutrino mass spectrum [14, 19].

The HEIDELBERG-MOSCOW experiment has been regularly continued in 2003. It had to be stopped, on November 30, 2003, according to contract. Unfortunately the Kurchatov institute did not agree to prolong the contract. The experiment is already since 2001 operated only by the Heidelberg group, which also performed the analysis of the experiment from its very beginning.

The experiment is *since ten years now* the most sensitive double beta experiment worldwide. In this report we will describe in section II the evidence for neutrinoless double beta decay ($0\nu\beta\beta$), found by an analysis of the HEIDELBERG-MOSCOW experiment including the three more years of data taking.

The result derived from the full data taken until May 20, 2003 is

$$T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25} \text{y} \quad (99.73\%c.l.) \quad (5)$$

with best value of $T_{1/2}^{0\nu} = 1.19 \times 10^{25} \text{y}$. Thus double beta decay is the slowest nuclear decay process observed until now in nature. Assuming the neutrino mass mechanism to dominate the decay amplitude, we deduce

$$\langle m_\nu \rangle = (0.24 - 0.58) \text{eV} \quad (99.73\%c.l.), \quad (6)$$

with best value of 0.44 eV. This value we obtained using the nuclear matrix element of [25]. Allowing for an uncertainty of $\pm 50\%$ of the matrix elements (see [5, 19]), this range widens to

$$\langle m_\nu \rangle = (0.1 - 0.9) \text{eV} \quad (7)$$

The result (2) and (3) determines the neutrino mass scenario to be degenerate [15, 20]. The common mass eigenvalue follows then to be $m_{com} = (0.14 - 3.6) \text{eV} \quad (99.73\%)$.

The new results with three more years of statistics confirm our earlier results [1, 2, 3, 4, 5, 7] on a higher confidence level. The signal is now seen on a 4.2σ level (see section 2).

If we allow for other mechanisms (see [17, 18, 19, 16]), the value given in eq. (6),(7) has to be considered as an upper limit. In that case very stringent limits arise for some other fields of beyond standard model physics. To give an example, it gives the sharpest limit on the Yukawa coupling λ'_{111} in the R-parity violating part of the superpotential [23]. It also gives information on R-parity conserving supersymmetry. New R-parity conserving SUSY contributions to $0\nu\beta\beta$ decay occur at the level of box diagrams [22]. Double beta decay then yields information on the mass splitting in the sneutrino-antisneutrino system [22]. These constraints leave room for accelerator searches for certain manifestations of the second and third generation (B-L)-violating sneutrino mass term, but are most probably too tight for first generation (B-L)-violating sneutrino masses to be searched for directly. It has been discussed recently [67] that $0\nu\beta\beta$ decay by R-parity violating SUSY experimentally may not be excluded, although this would require making R-parity violating couplings generation dependent.

We show, in section III that indirect support for the observed evidence for neutrino-less double beta decay evidence comes from analysis of other Ge double beta experiments (though they are by far less sensitive, they yield independent information on the background in the region of the expected signal).

Table 1: Recent support of the neutrino mass deduced from $0\nu\beta\beta$ decay [1, 2, 5, 12, 11] by other experiments, and by theoretical work.

Experiment	References	m_ν (degenerate ν 's)(eV)
$0\nu\beta\beta$	[1, 2, 5, 12, 11]	0.05 - 3.2
WMAP	[75, 77]	< 0.23, or 0.33, or 0.50
CMB	[74]	< 0.7
CMB+LSS+X-ray gal. Clust.	[79]	~ 0.2 eV
SDSS + WMAP	[84]	< 0.57 eV
Z - burst	[65, 73]	0.08 - 1.3
g-2	[66]	> 0.2
Tritium	[54]	< 2.2 - 2.8
ν oscillation	[69, 70]	> 0.04
Theory:		
A ₄ -symmetry identical quark	[71]	> 0.2
and ν mixing at GUT scale	[72]	> 0.1
Alternative cosmological 'concordance model'	[80]	order of eV

The discussion in section IV, V, VI, may now just still be of historical interest. Here we disprove some criticism of our *earlier* given results. We show by measurements with a ^{226}Ra source, performed in 2003 [12], and by various statistical calculations, that the criticism by Aalseth et al., (see Mod. Phys. Lett. A17 (2002) 1475-1478), Zdesenko et

al., (see Phys. Lett. B 546 (2002) 206-215), Ianni (in NIM 2004), Feruglio et al., (see Nucl. Phys. B 637 (2002) 345) of our earlier results [1, 2, 5] just was *wrong*.

In section VII we give a short discussion, stressing that the evidence for neutrinoless double beta decay has been supported by various recent experimental results from other fields of research (see Table 1). It is consistent [20] with recent results from cosmic microwave background experiments [74, 75, 77]. The precision of WMAP even allows to rule out some old-fashioned nuclear double beta decay matrix elements (see [76]).

It has been shown to be consistent with the neutrino masses required for the Z-burst scenarios of high-energy cosmic rays [73, 65]. It is consistent with a (g-2) deviating from the standard model expectation [66]. It is consistent also with the limit from the tritium decay experiments [45] but the allowed confidence range still extends down to a range which cannot be covered by future tritium experiments (apart from some principle theoretical problems, which tritium decay may have to see neutrino masses [81]. It is further supported by recent theoretical work [71, 72, 83].

Cosmological experiments like WMAP are now on the level that they can seriously contribute to terrestrial research. The fact that WMAP and less strictly also the tritium experiments cut away the upper part of the allowed range for the degenerate neutrino mass ($m_{com} = (0.14 - 3.6) eV$) could indicate that the neutrino mass eigenvalues have the same CP parity [21].

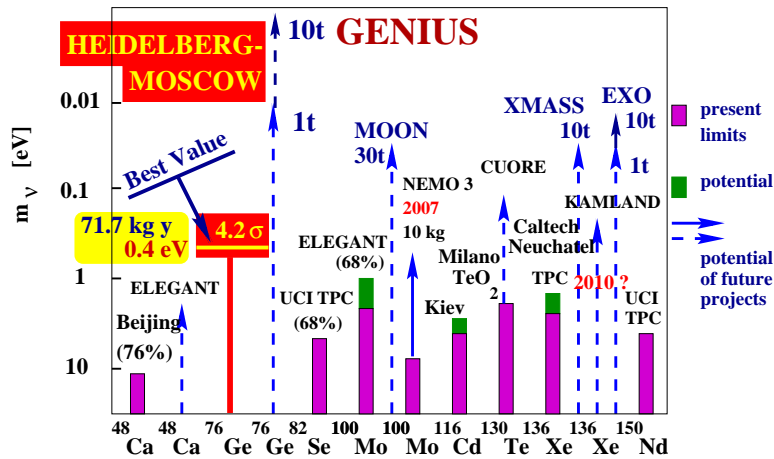


Figure 1: Present sensitivity, and expectation for the future, of the most promising $\beta\beta$ experiments. Given are limits for $\langle m \rangle$, except for the HEIDELBERG-MOSCOW experiment where the measured *value* is given (3σ c.l. range and best value). Framed parts of the bars: present status; not framed parts: future expectation for running experiments; solid and dashed lines: experiments under construction or proposed, respectively. For references see [19, 2, 5, 61, 59].

Finally we briefly comment in section VIII about the possible future of the field of double beta decay. First results from GENIUS-TF which has come into operation on May 5, 2003 in Gran Sasso with first in world 10 kg of naked Germanium detectors in liquid nitrogen [50, 52, 51], are discussed in another contribution to this report [48].

(see section 6). Analysis of the spectra by nonlinear least squares method, using the Levenberg-Marquardt algorithm yields the fits, shown in Fig. 3.

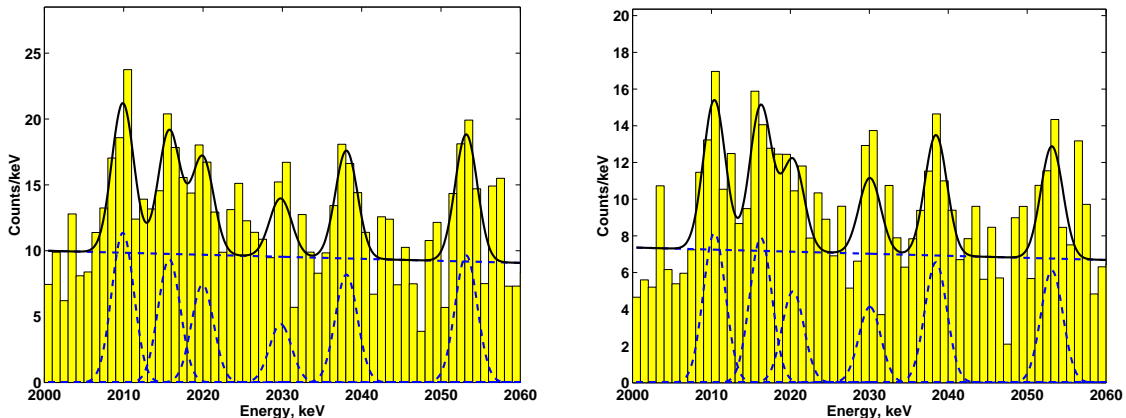


Figure 3: The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period August 1990 to May 2003 (71.7 kg y) left, and for the period November 1995-2003 (56.66 kg y) in the range 2000 - 2060 keV and its fit (see section 3.2).

In these fits the peak positions, widths and intensities of all lines are determined simultaneously, and also the absolute level of the background. The shape of the latter was chosen to be slightly decreasing with energy, corresponding to the complete simulation of the background performed in [13] by GEANT4. E.g. in Fig. 3, right, the *fitted* background corresponds to (55.94 ± 3.92) kg y if extrapolated from the background *simulated* in [13] for the measurement with 49.59 kg y of statistics (see Fig. 15). This is almost *exactly* the statistical significance of the present experiment (56.66 kg y) and thus a very nice proof of consistency. Assuming a *constant* background in the range 2000 - 2060 keV or keeping also the *slope* of a linearly varying background as a free parameter, yields very similar results. Analysis with the Maximum Likelihood Method gives results consistent with the above method.

The signal at $Q_{\beta\beta}$ in the full spectrum (the fit of Fig. 3, right, yields 2038.44 ± 0.45 keV), reaches a 4.2σ confidence level for the period 1990-2003, and of 4.1σ for the period 1995-2003 (for details we refer to [6]. A detailed description of the analysis of the full data 1990-2003 will be given in the next Annual Report.

3 Measurements With a ^{214}Bi Source, Comparison With Other Ge-Experiments

By the peak search procedure developed [2, 5] on basis of the Bayes and Maximum Likelihood Methods, exploiting as important input parameters the experimental knowledge on the shape and width of lines in the spectrum, weak lines of ^{214}Bi had been identified at the energies of 2010.7, 2016.7, 2021.6 and 2052.9 keV already in [1, 2, 5, 10]. Though the lines with our improved statistics and analysis are now clearly seen directly in the spectrum (Fig. 3), we show for comparison the result of the peak search procedure for the spectrum taken 1995-2003, in Fig. 4. As usual, shown is the probability that there is

a line of correct width and of Gaussian shape at a given energy, assuming all the rest of the spectrum as flat background (which is a highly conservative assumption).

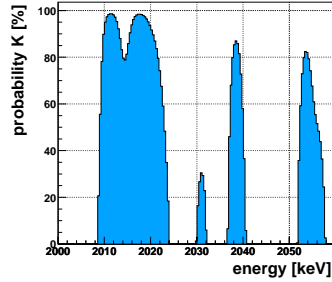


Figure 4: Scan for lines in the full spectrum taken from 1995 - 2003 with detectors Nr. 1,2,3,4,5, with the MLM method (see text). The Bi lines at 2010.7, 2016.7, 2021.8 and 2052.9 keV are clearly seen, and in addition a signal at ~ 2039 keV.

Concerning the intensities of these ^{214}Bi lines, one has to note that the 2016 keV line, as an E0 transition, can be seen only by coincident summing of the two successive lines $E = 1407.98$ keV and $E = 609.316$ keV. Its observation proves that the ^{238}U impurity from which it is originating, is located in the Cu cap of the detectors.

We performed, in the first half of 2003, a *measurement* of a ^{226}Ra source with a high-purity germanium detector [12]. The aim of this work was to investigate the difference in the Bi spectra when changing the position of the source with respect to the detector, and to verify the effect of TCS (true coincidence summing) for the weak ^{214}Bi lines seen in the HEIDELBERG-MOSCOW experiment .

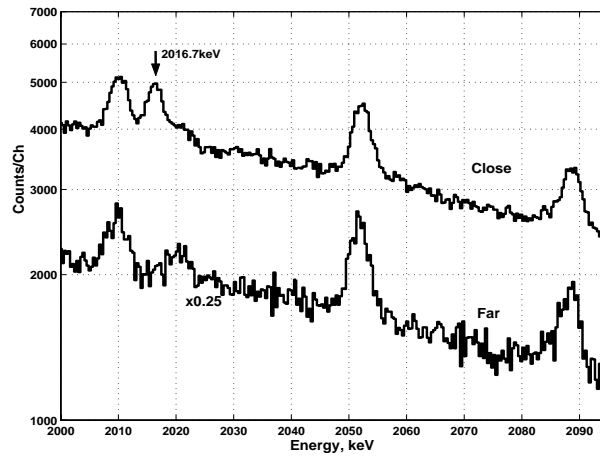


Figure 5: Measured ^{226}Ra spectrum in the energy range from 2000 to 2100 keV. The upper spectrum corresponds to the close geometry, the bottom spectrum to the far geometry. The weak lines from ^{214}Bi are nicely visible, together with the effect of the true coincidence summing at 2016.7 keV (from [12]).

The activity of the ^{226}Ra source was 95.2 kBq. The isotope ^{226}Ra appears in the ^{238}U natural decay chain and from its decays also ^{214}Bi is produced. The γ -spectrum of

^{214}Bi is clearly visible in the ^{226}Ra measured spectrum (see Fig. 5). We also performed a simulation of our measurement with the GEANT4 simulation tool and we find good agreement between the simulation and the measurement [12]. The premature estimates of the Bi intensities given in *Aalseth et al.*, hep-ex/0202018 and Feruglio et al., Nucl. Phys. B 637 (2002), 345, *are incorrect*, because this long-known spectroscopic effect of true coincident summing [27] has not been taken into account, and also no simulation of the setup has been performed (for details see [5, 3, 9, 12, 7]).

These Bi lines occur also in other investigations of double beta decay. There are three other Ge experiments which have looked for double beta decay of ^{76}Ge . First there is the experiment by Caldwell et al. [34], using natural Germanium detectors (7.8% abundance of ^{76}Ge , compared to 86% in the HEIDELBERG-MOSCOW experiment). This was the most sensitive *natural* Ge experiment. With their background a factor of 9 higher than in the HEIDELBERG-MOSCOW experiment and their measuring time of 22.6 kg years, they had a statistics of the background by a factor of almost four l a r g e r than in the HEIDELBERG-MOSCOW experiment. This gives useful information on the composition of the background.

Applying the same method of peak search as used in Fig. 4, yields (see also [7, 11]) indications for peaks essentially at the same energies as in Fig. 4 (see Fig. 6). This shows that these peaks are not fluctuations. In particular it sees the 2010.78, 2016.7, 2021.6 and 2052.94 keV ^{214}Bi lines, but a l s o the unattributed lines at higher energies. It finds, however, n o line at 2039 keV. This is consistent with the expectation from the rate found in the HEIDELBERG-MOSCOW experiment. About 29 identified events observed during 1990-2003 in the latter correspond to 0.7 expected events in the Caldwell experiment, because of the use of non-enriched material and the shorter measuring time. Fit of the Caldwell spectrum allowing for the ^{214}Bi lines and a 2039 keV line yields 0.4 events for the latter (see [5] and Fig. 9).

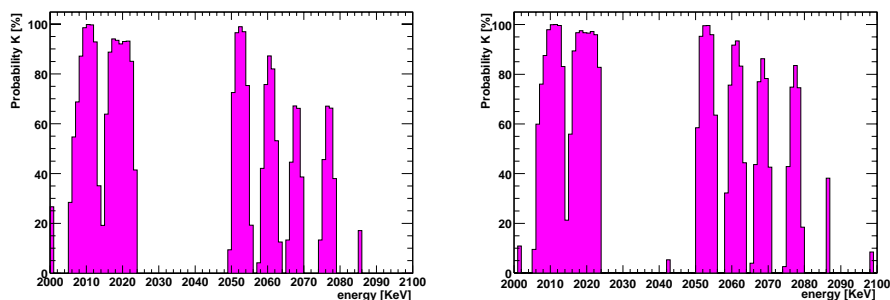


Figure 6: Result of the peak-search procedure performed for the UCBS/LBL spectrum [34] (left: Maximum Likelihood method, right: Bayes method). On the y axis the probability of having a line at the corresponding energy in the spectrum is shown (from [7, 11]).

The first experiment using enriched (but not high-purity) Germanium 76 detectors was that of Kirpichnikov and coworkers [35]. These authors show only the energy range between 2020 and 2064 keV of their measured spectrum. The peak search procedure finds also here indications of lines around 2028 keV and 2052 keV (see Fig. 7), but n o t any indication of a line at 2039 keV. This is consistent with the expectation, because for

their low statistics of 2.95 kg y they would expect here (according to HEIDELBERG-MOSCOW) 1.1 counts.

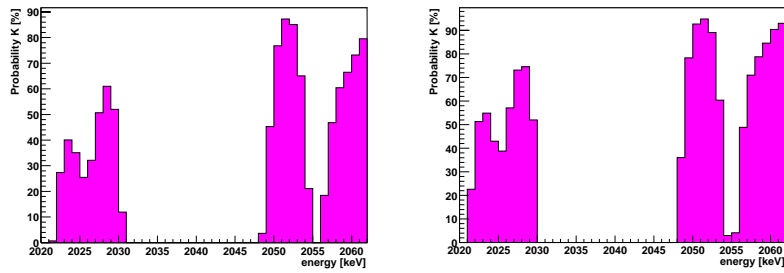


Figure 7: Result of the peak-search procedure performed for the ITEP/YePI spectrum [35] (from [7, 11]).

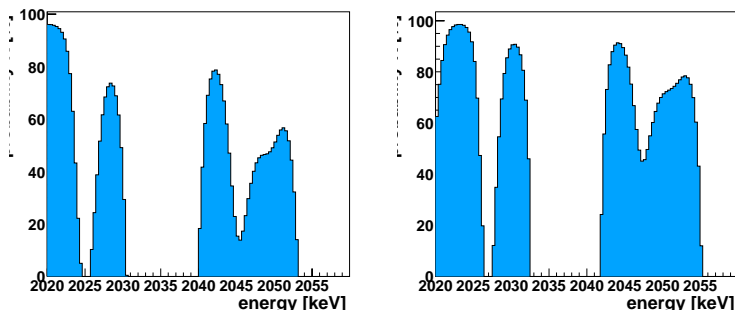


Figure 8: Result of the peak-search procedure performed for the IGEX spectrum [57]. Left: Maximum Likelihood method, right: Bayes method. On the y axis the probability of having a line at the corresponding energy in the spectrum is shown (from [7, 11]).

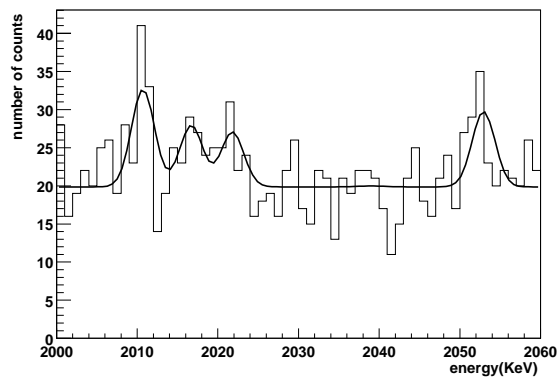


Figure 9: Analysis of the spectrum measured by D. Caldwell et al. [34], with the Maximum Likelihood Method, in the energy range 2000-2060 keV assuming lines at 2010.7, 2016.7, 2021.6, 2052.9, 2039.0 keV. No indication for a signal at 2039 keV is observed in this case (see [7]).

Another experiment (IGEX) used between 6 and 8.8 kg of enriched ^{76}Ge , but collected since beginning of the experiment in the early nineties till shutdown in 1999 only 8.8 kg years of statistics [57]. The authors of [57] unfortunately show only the range 2020 to 2060 keV of their measured spectrum in detail. Fig. 8 shows the result of our peak scanning of this range. Clear indications are seen for the lines at 2021 and 2052 keV, but also of the unidentified structure around 2030 keV. Because of the conservative assumption on the background treatment in the scanning procedure (see above) there is no chance to see a signal at 2039 keV because of the 'hole' in the background of that spectrum (see Fig. 1 in [57]). With some good will one might see, however, an indication of ~ 3 events here, consistent with the expectation of the HEIDELBERG-MOSCOW experiment of ~ 2.6 counts.

4 Statistical Features: Sensitivity of Peak Search, Analysis Window

For historical reasons, at this point it may be useful to demonstrate the potential of the peak search procedure used in [1, 2, 5]. Fig. 10 shows a spectrum with Poisson-generated background of 4 events per channel and a Gaussian line with width (standard deviation) of 4 channels centered at channel 50, with intensity of 10 (left) and 100 (right) events, respectively. Fig. 12, shows the result of the analysis of spectra of different line intensity with the Bayes method (here Bayes 1-4 correspond to different choice of the prior distribution: (1) $\mu(\eta) = 1$ (flat), (2) $\mu(\eta) = 1/\eta$, (3) $\mu(\eta) = 1/\sqrt{\eta}$, (4) Jeffrey's prior) and the Maximum Likelihood Method. For each prior 1000 spectra have been generated with equal background and equal line intensity using random number generators available at CERN [24]. The average values of the best values agree (see Fig. 12) very well with the known intensities also for very low count rates (as in Fig. 10, left).

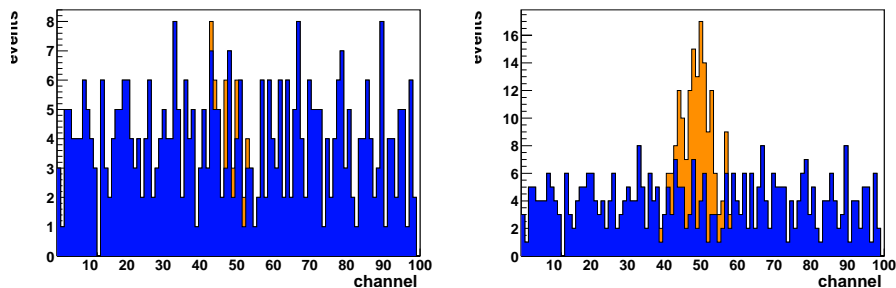


Figure 10: Example of a random-generated spectrum with a Poisson distributed background with 4.0 events per channel and a Gaussian line centered in channel 50 (line-width corresponds to a standard-deviation of $\sigma = 4.0$ channels). The left picture shows a spectrum with a line-intensity of 10 events, the right spectrum a spectrum with a line-intensity of 100 events. The background is shown dark, the events of the line bright (see [11]).

In Fig. 13 we show two simulations of a Gaussian line of 15 events, centered at channel 50, again with width (standard deviation) of 4 channels, on a Poisson-distributed background with 0.5 events/channel. The figure gives an indication of the possible degree of deviation of the energy of the peak maximum from the transition energy, on the level of

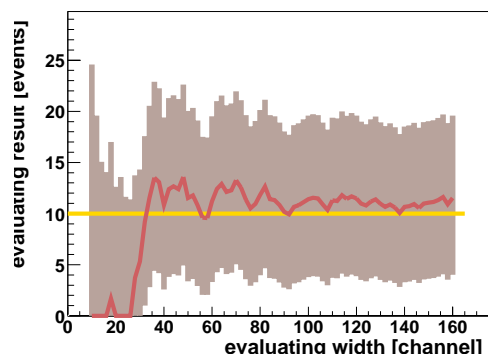


Figure 11: Result of an analysis as function of the evaluation width. The used spectrum consists of a Poisson distributed background with 4 events per channel, and a line of 10 events (see Fig. 10, left part). The dark area corresponds to a 68.3% confidence area with the dark line being the best value. Below an evaluation width of 35 channels the result becomes unreliable, above 35 channels the result is stable (see also [7, 11]).

statistics collected in experiments like the HEIDELBERG-MOSCOW experiment (here one channel corresponds to 0.36 keV). This should be kept in mind.

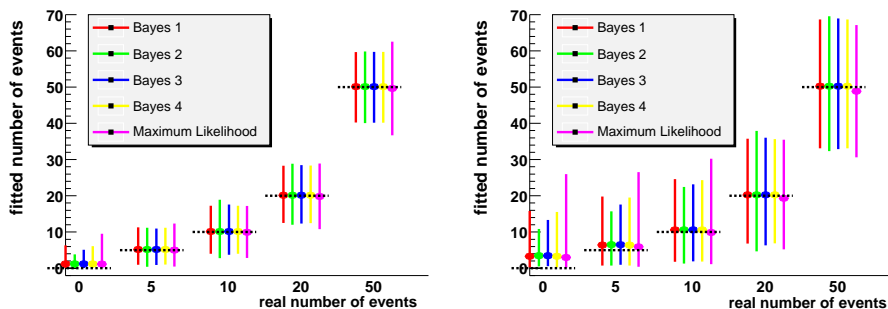


Figure 12: Results of analysis of random-number generated spectra, using Bayes and Maximum Likelihood method (the first one with different prior distributions). For each number of events in the simulated line, shown on the x-axis, 1000 random generated spectra were evaluated with the five given methods. The analysis on the left side was performed with an Poisson distributed background of 0.5 events per channel, the background for the spectra on the right side was 4.0 events per channel. Each vertical line shows the mean value of the calculated best values (thick points) with the 1σ error area. The mean values are in good agreement with the expected values (horizontal black dashed lines) (see [7, 11]).

The influence of the choice of the energy range of the analysis around $Q_{\beta\beta}$ has been thoroughly discussed in [2, 5]. Since erroneous ideas about this point are still around, let us remind of the analysis given in [2, 5, 11, 7] which showed that a reliable result is obtained for a range of analysis of not smaller than 35 channels (i.e. ± 18 channels) - one channel corresponding to 0.36 keV in the HEIDELBERG-MOSCOW experiment (see Fig. 11). This is an important result, since it is, in case of a weak signal, *of course* important to keep the range of analysis as small as possible, to avoid to include lines in the vicinity of the weak signal into the background (see, e.g. Fig. 9 in [82]). This unavoidably occurs

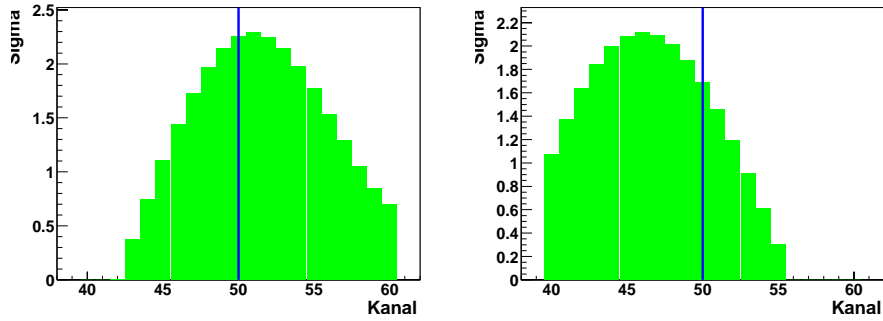


Figure 13: Two spectra with a Poisson-distributed background and a Gaussian line with 15 events centered in channel 50 (with a width (standard-deviation) of 4.0 channels) created with different random numbers. Shown is the result of the peak-scanning of the spectra. In the left picture the maximum of the probability corresponds well with the expected value (black line) whereas in the right picture a larger deviation is found. When a channel corresponds to 0.36 keV the deviation in the right picture is ~ 1.44 keV (see [7, 11]).

when e.g. proceeding as suggested in F. Feruglio et al., hep-ph/0201291 and Nucl. Phys. B 637 (2002) 345-377, Aalseth et. al., hep-ex/0202018 and Mod. Phys. Lett. A 17 (2002) 1475, Yu.G. Zdesenko et. al., Phys. Lett. B 546 (2002) 206, A. Ianni, in Press NIM 2004. The arguments given in those papers are therefore *incorrect*. Also Kirpichnikov, who states [35] that his analysis finds a 2039 keV signal in the HEIDELBERG-MOSCOW spectrum on a 4 sigma confidence level (as we also see it) makes this mistake, when analysing the pulse shape spectrum.

The above discussion is now in this context only of historical interest, since with the better statistics we have now, we can analyze simultaneously a large energy range (as shown in Fig. 3).

5 Simulation with GEANT4

Finally the background around $Q_{\beta\beta}$ will be discussed from the side of simulation. A very careful new simulation of the different components of radioactive background in the HEIDELBERG-MOSCOW experiment has been performed by a new Monte Carlo program based on GEANT4 [13]. This simulation uses a new event generator for simulation of radioactive decays basing on ENSDF-data and describes the decay of arbitrary radioactive isotopes including alpha, beta and gamma emission as well as conversion electrons and X-ray emission. Also included in the simulation is the influence of neutrons in the energy range from thermal to high energies up to 100 MeV on the measured spectrum. Elastic and inelastic reactions, and capture have been taken into account, and the corresponding production of radioactive isotopes in the setup. The neutron fluxes and energy distributions were taken from published measurements performed in the Gran Sasso. Also simulated was the cosmic muon flux measured in the Gran Sasso, on the measured spectrum. To give a feeling for the quality of the simulation, Fig. 14 shows the simulated and the measured spectra for a ^{228}Th source spectrum for as example one of our five detectors. The agreement is excellent.

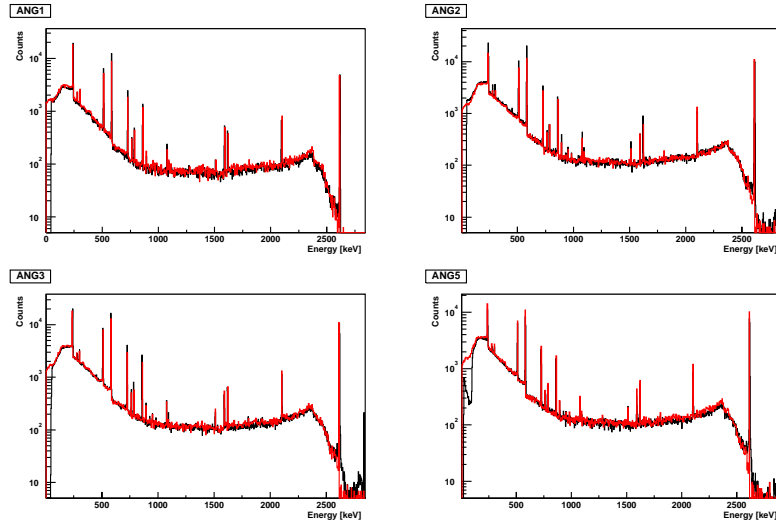


Figure 14: Comparison of the measured data (black line, November 1995 to April 2002) and simulated spectrum (red line) for the detectors Nrs. 1,2,3 and 5 for a ^{232}Th source spectrum. The agreement of simulation and measurement is excellent (from [13]).

The simulation of the background of the experiment reproduces all lines observed in the sum spectrum of the five detectors, in the energy range between threshold (around 100 keV) and 2020 keV [13].

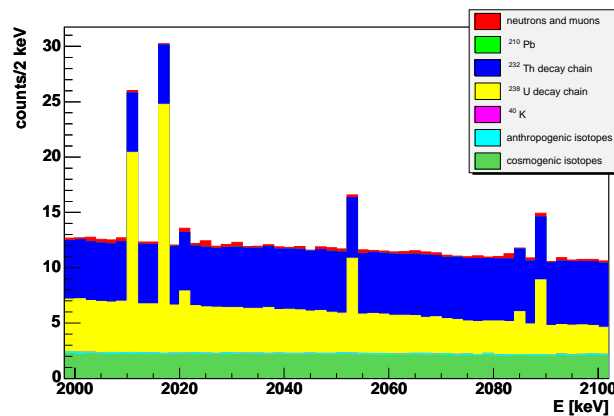


Figure 15: Simulated background of the HEIDELBERG-MOSCOW experiment in the energy range from 2000 to 2100 keV with all known background components, for the period 20 November 1995 to 16 April 2002 (from [13]).

Fig. 15 shows the simulated background in the range 2000-2100 keV with all known background components.

The background around $Q_{\beta\beta}$ is according to the simulations flat, the only expected lines come from ^{214}Bi (from the ^{238}U natural decay chain) at 210.89, 216.7, 221.6, 2052.94, 2085.1 and 2089.7 keV. Lines from cosmogenically produced ^{56}Co (at 2034.76 keV and 2041.16 keV), half-life 77.3 days, are not expected since the first 200 days of measurement of each detector are not used in the data analysis. Also the potential contribution

from decays of ^{77}Ge , ^{66}Ga , or ^{228}Ac , should not lead to signals visible in our measured spectrum near the signal at $Q_{\beta\beta}$. For details we refer to [13].

6 Proofs and disproofs

Our earlier result published in [1, 2, 5], which now is confirmed on a 4σ level, had been questioned in some papers [Aalseth et al, hep-ex/0202018, and in Mod. Phys. Lett. A 17 1475-1478; Feruglio et al., Nucl. Phys. B 637 (2002) 345; Zdesenko et al., Phys. Lett. B 546 (2002) 206], and Kirpichnikov, talk at Meeting of Physical Section of Russian Academy of Sciences, Moscow, December 2, 2002, (and priv. communication, Dec. 3, 2002) and A. Ianni, Nucl. Instruments A (2004) (available online 28 September 2003). We think that we have shown in a convincing way during 2002 and 2003 that these claims against our results were incorrect in various ways, and have published our arguments in [12, 11, 7, 10]. In particular the estimates of the intensities of the ^{214}Bi lines in the first two papers do not take into account the effect of true coincidence summing, which can lead to drastic underestimation of the intensities. A correct estimate would also require a Monte Carlo simulation of our setup, which has not been performed in the above papers.

The paper by Zdesenko et al. starts from an arbitrary assumption, namely that there are lines in the spectrum *at best* only at 2010 and 2053 keV. This contradicts to the experimental result, according to which there are further lines in the spectrum (see Fig. 3 in this report). For example they could have easily deduced from the intensity of the 2204 keV Bi line in the measured spectrum (Fig. 2) that lines at 2053 keV etc. are expected [32]. In this way and also by some subtraction procedure, ignoring that the result of subtracting a Poisson-distributed spectrum from a Poisson-distributed spectrum does *not* give a Poisson distributed spectrum (see, e.g. [33]) they come to wrong conclusions.

Kirpichnikov states [36] that from his analysis he clearly sees the 2039 keV line in the full (not pulse-shape discriminated) spectrum on a 4σ level. He claims that he does not see the signal in the pulse shape spectrum. The simple reason to see less intensity is that in this case he averages for determination of the background over the full energy range without allowing for any lines.

All of these papers, when discussing our earlier choice of the width of the search window (in the analysis of the data taken until May 2000), ignore the results of the statistical simulations - we present here, and have published in [2, 3, 4, 5, 7, 10, 11].

The strange effects found recently by the Kurchatov people [55] in their rough analysis of part of the data, have been traced back to including corrupt data into the analysis. The artefacts seen in their Figs. 4,5,7,8 do not exist in our data, which lead to the results shown in Figs. 2,3 (for details see [6, 56]).

7 Discussion of results

We emphasize that we find in all analyses of our spectra a line at the value of $Q_{\beta\beta}$. The results confirm our earlier result with higher statistics. For details we refer to the next Annual Report and to [6].

The result obtained is consistent with all other double beta experiments - which reach in general by far less sensitivity. The most sensitive experiments following the

HEIDELBERG-MOSCOW experiment are the geochemical ^{128}Te experiment with $T_{1/2}^{0\nu} > 2(7.7) \times 10^{24}$ y (68% c.l.), [37] the ^{136}Xe experiment by the DAMA group with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$ y (90% c.l.), a second enriched ^{76}Ge experiment with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$ y [35] and a ^{nat}Ge experiment with $T_{1/2}^{0\nu} > 1 \times 10^{24}$ y [34]. Other experiments are already about a factor of 100 less sensitive concerning the $0\nu\beta\beta$ half-life: the Gotthard TPC experiment with ^{136}Xe yields [38] $T_{1/2}^{0\nu} > 4.4 \times 10^{23}$ y (90% c.l.) and the Milano Mibeta cryodetector experiment $T_{1/2}^{0\nu} > 1.44 \times 10^{23}$ y (90% c.l.).

Another experiment [57] with enriched ^{76}Ge , which has stopped operation in 1999 after reaching a significance of 8.8 kg y, yields (if one believes their method of 'visual inspection' in their data analysis), in an analysis correcting for an arithmetic error which has been made in [57] (for discussion see [58]) a limit of about $T_{1/2}^{0\nu} > 5 \times 10^{24}$ y (90% c.l.). The ^{128}Te geochemical experiment yields $\langle m_\nu \rangle < 1.1$ eV (68 % c.l.) [37], the DAMA ^{136}Xe experiment $\langle m_\nu \rangle < (1.1-2.9)$ eV and the ^{130}Te cryogenic experiment yields $\langle m_\nu \rangle < 1.8$ eV.

Concluding we obtain, with $> 4\sigma$ probability, evidence for a neutrinoless double beta decay signal. Following this interpretation, at this confidence level, lepton number is not conserved. Further the neutrino is a Majorana particle. If the $0\nu\beta\beta$ amplitude is dominated by exchange of a massive neutrino the effective mass $\langle m \rangle$ is deduced from the full spectrum (using the matrix elements of [25]) to be $\langle m \rangle = (0.1 - 0.9)$ eV (3σ confidence range), allowing already for a $\pm 50\%$ uncertainty of the matrix element. The best value is 0.4 eV.

Assuming other mechanisms to dominate the $0\nu\beta\beta$ decay amplitude, 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. For a discussion and for references we refer to [19, 39, 42, 18, 59, 16].

With the value deduced for the effective neutrino mass, the HEIDELBERG-MOSCOW experiment excludes several of the neutrino mass scenarios allowed from present neutrino oscillation experiments (see Fig. 16) - allowing only for a degenerate mass scenario [15, 20, 6]. Fig. 16 shows also the limits obtained from WMAP, which at the present level of sensitivity is not able to rule out any neutrino mass scheme.

The evidence for neutrinoless double beta decay has been supported by various recent experimental and theoretical results (see Table 1). Assuming the degenerate scenarios to be realized in nature we fix - according to the formulae derived in [14] - the common mass eigenvalue of the degenerate neutrinos to $m = (0.1 - 3.6)$ eV. Part of the upper range is excluded by tritium experiments, which give a limit of $m < (2.2 - 2.8)$ eV (95% c.l.) [45]. The full range can only partly (down to ~ 0.5 eV) be checked by future tritium decay experiments, but might be checked by some future $\beta\beta$ experiments (see next section). Recent theoretical work [81] even doubts, that tritium experiments are in *principle* capable to check a $0\nu\beta\beta$ result. The deduced best value for the mass is consistent with expectations from experimental $\mu \rightarrow e\gamma$ branching limits in models assuming the generating mechanism for the neutrino mass to be also responsible for the recent indication for an anomalous magnetic moment of the muon [66]. It lies in a range of interest also for Z-burst models recently discussed as explanation for super-high energy cosmic ray events beyond the GKZ-cutoff [65, 73] and requiring neutrino masses in the range (0.08 - 1.3)

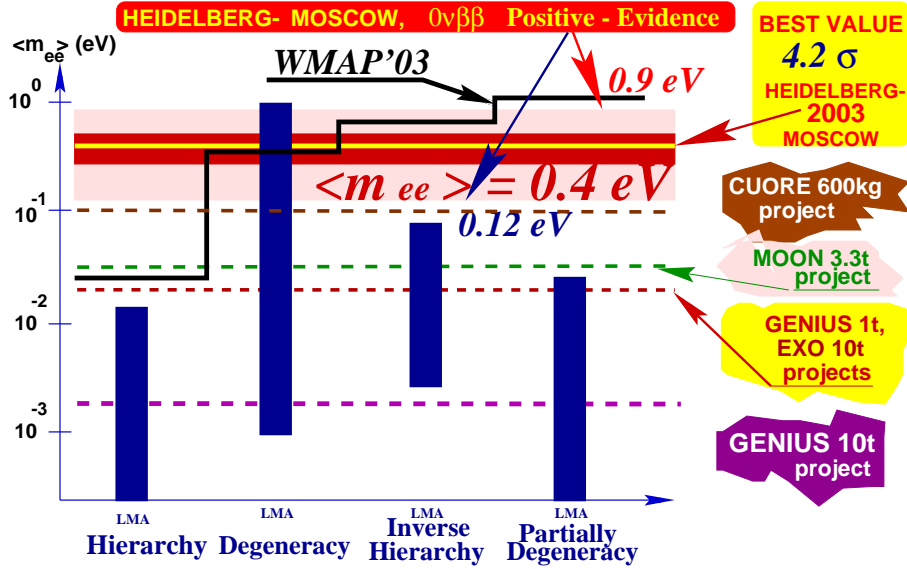


Figure 16: The impact of the evidence obtained at (4.2σ c.l.) for neutrinoless double beta decay (best value of the effective neutrino mass $\langle m \rangle = 0.4 eV$, 3σ confidence range ($0.1 - 0.9$) eV - allowing already for an uncertainty of the nuclear matrix element of a factor of $\pm 50\%$) 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 [15, 20]). 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 $\sum m_\nu < 1.0 eV$ [77]. 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 [19, 18, 60, 41] (from [20]).

eV. A recent model with underlying A_4 symmetry for the neutrino mixing matrix also leads to degenerate Majorana neutrino masses $> 0.2 eV$, consistent with the present result from $0\nu\beta\beta$ decay [68, 71]. The result is further consistent with the theoretical paper of [72]. Starting with the hypothesis that quark and lepton mixing are identical at or near the GUT scale, Mohapatra et al. [72] show that the large solar and atmospheric neutrino mixing angles can be understood purely as result of renormalization group evolution, if neutrino masses are quasi-degenerate (with same CP parity). The common Majorana neutrino mass then must be, in this model, larger than $0.1 eV$. An completely independent theoretical proof, that neutrinos should have Majorana nature, has been given recently by [83].

For WMAP a limit for the sum of the neutrino masses of $m_s = \sum m_i < 0.69 eV$ at 95% c.l., was given by the analysis of ref. [75]. More realistically this limit on the total mass should be [77] $m_s = \sum m_i < 1.0 eV$ at 95% c.l. The latter analysis also shows, that four generations of neutrinos are still allowed and in the case of four generations the limit on the total mass is increased to $1.38 eV$. If there is a fourth neutrino with very small mass, then the limit on the total mass of the three neutrinos is even further weakened and there is essentially no constraint on the neutrino masses. In our Fig. 16 we show the contour

line for WMAP assuming $\sum m_i < 1.0$ eV.

A recent analysis of the Sloan Digital Sky Survey, together with WMAP yields [84]

$$m_s = \sum m_i < 1.7 \text{ eV} \quad \text{at } 2\sigma. \quad (8)$$

Comparison of the WMAP results with the effective mass from double beta decay rules out completely (see [76]) a 15 years old old-fashioned nuclear matrix element of double beta decay, used in a recent analysis of WMAP [78]. In that calculation of the nuclear matrix element there was not included a realistic nucleon-nucleon interaction, which has been included by all other calculations of the nuclear matrix elements over the last 15 years.

The range of $\langle m \rangle$ fixed in this work is, in the range to be explored by the satellite experiments MAP and PLANCK [14, 75, 77]. The limitations of the information from WMAP are seen in Fig. 16, thus results of PLANCK are eagerly awaited.

The neutrino mass deduced leads to $0.002 \geq \Omega_\nu h^2 \leq 0.1$ and thus may allow neutrinos to still play an important role as hot dark matter in the Universe [47].

8 Future of $\beta\beta$ experiments

With the HEIDELBERG-MOSCOW experiment, the era of the small smart experiments is over. New approaches and considerably *enlarged experiments* (as discussed, e.g. in [17, 39, 19, 42, 60, 41, 44, 47]) will be required in future to fix the $0\nu\beta\beta$ half life of ^{76}Ge with higher accuracy. This will, however, because of the uncertainties in the nuclear matrix elements, which probably hardly *can* be reduced to less than 50%, *only marginally reduce* the precision of the deduced neutrino mass.

Since it was realized in the HEIDELBERG-MOSCOW experiment, that the remaining small background is coming from the material close to the detector (holder, copper cap, ...), elimination of *any* material close to the detector will be decisive. Experiments which do not take this into account, will allow at best only rather limited steps in sensitivity. Furthermore there is the problem in cryodetectors that they *cannot* differentiate between a β and a γ signal, as this is possible in Ge experiments.

Another crucial point is the energy resolution, which can be optimized *only* in experiments using Germanium detectors, or, to some less extent, with bolometers. It will be difficult to probe evidence for this rare decay mode in experiments, which have to work - as result of their limited resolution - with energy windows around $Q_{\beta\beta}$ of several hundreds of keV.

Another important point is the efficiency of a detector for detection of a $\beta\beta$ signal. For example, with 14% efficiency a potential future 100 kg ^{82}Se experiment would be, because of its low efficiency, equivalent only to a 10 kg experiment (not talking about the energy resolution).

In the first proposal for a third generation double beta experiment, our GENIUS proposal [39, 17, 40, 42, 60, 41], the idea is to use 'naked' Germanium detectors in a huge tank of liquid nitrogen. It seems to be at present the *only* proposal, which can fulfill *both* requirements mentioned above - to increase the detector mass and simultaneously reduce the background drastically. At the *present* status of results of the HEIDELBERG-MOSCOW experiment, however - with a confidence level of $\sim 4\sigma$, it is *questionable*, whether GENIUS would be needed for $\beta\beta$ decay. Probably it would be preferable to

perform an experiment with another isotope *but fulfilling* all requirements mentioned above. The GENIUS-Test-Facility, originally planned to prove the feasibility of some key constructional parameters of GENIUS, and put into operation on May 5, 2003 in GRAN SASSO, could however, play an important role in testing the evidence seen [63] for cold dark matter by DAMA (see [50, 52], and another Report to this volume). Only a GENIUS with some ten tons of enriched ^{76}Ge might possibly be of interest, to investigate whether another exotic mechanism such as exchange of SUSY particles, (see, e.g. [19]) might contribute to the $0\nu\beta\beta$ decay amplitude. This may be, however, a very far dream.

9 Summary

The HEIDELBERG-MOSCOW experiment has been continued regularly in 2003. Unfortunately, it had to stop operation according to non-prolongation of our contract with Kurchatov institute, at 30 November 2003. Since then still various calibration measurements with radioactive sources are going on.

The first analysis of the full data taken with the HEIDELBERG-MOSCOW experiment in the period 2 August 1990 until 20 May 2003 is presented. The improved statistics and data analysis leads to a $\sim 4\sigma$ evidence for a signal at the Q-value for neutrinoless double beta decay. This confirms our earlier claim [1, 2, 5, 6]. Additional support for this evidence has been presented by showing consistency of the result - for the signal, a n d for the background - with other double beta decay experiments using non-enriched or enriched Germanium detectors (see also [7, 11]). In particular it has been shown that the lines seen in the vicinity of the signal are seen also in the other experiments. This is important for the correct treatment of the background. Furthermore, the sensitivity of the peak identification procedures has been demonstrated by extensive statistical simulations. It has been further shown by new extensive simulations of the expected background by GEANT4, that the background around $Q_{\beta\beta}$ should be flat, and that no known gamma line is expected at the energy of $Q_{\beta\beta}$ (see [13]). The 2039 keV signal is seen o n l y in the HEIDELBERG-MOSCOW experiment, which has a *by far larger* statistics than all other double beta experiments.

The importance of first evidence for violation of lepton number and of the Majorana nature of neutrinos is obvious. It requires beyond Standard Model Physics on one side, and may open a new era in space-time structure [62]. 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.

One of the consequences of the result of the HEIDELBERG-MOSCOW experiment on the present confidence level, may be, that to obtain *deeper* information on the process of neutrinoless double beta decay, *new experimental approaches, different from all, what is at present persued*, may be required. The unique importance of double beta decay to investigate the neutrino mass, is stressed by the recent observation, that tritium experiments might suffer from principle problems to see a neutrino mass at all [81].

With the successful start of operation of GENIUS-TF with the first four naked Ge detectors in liquid nitrogen on May 5, 2003 in GRAN SASSO, which is described in [49, 50] (see our second contribution to this Report) a historical step has been achieved of a novel technique and into a new domain of background reduction in underground physics in the

search for rare events. In the light of the above comments, natural task of GENIUS-TF will be to look for cold dark matter by the modulation signal.

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List of Edited Proceedings (2003)

1. H.V. Klapdor-Kleingrothaus (ed.) *Physics Beyond the Standard Model: Beyond the Desert 02*, Proc. of Intern. Conf. BEYOND'02, Oulu, Finland, 2-7 Jun 2002, IOP, Bristol, 2003, 734 pages.
2. H.V. Klapdor-Kleingrothaus (ed.) *Physics Beyond the Standard Model: Beyond the Desert 03*, Proc. of Intern. Conf. BEYOND'03, Tegernsee, Germany, 4-9 June 2003, Springer, Heidelberg, 2004 (in preparation).

List of Publications (2003)

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3. H.V. Klapdor-Kleingrothaus, Fachbereich Physik, Bergische Universität Wuppertal, Germany 26 May 2003, "*The Absolute Neutrino Mass After the First Evidence for Neutrinoless Double Beta Decay*".

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5. H.V. Klapdor-Kleingrothaus, Osaka University, Japan, 17 February 2003, "*First Evidence for Neutrinoless Double Beta Decay from the HEIDELBERG-MOSCOW Experiment and Implication for Particle Physics and Astrophysics*".
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