Double beta decay is indispensable to solve the question of the neutrino mass matrix together with neutrino oscillation experiments. Recent analysis of the most sensitive experiment since eight years - the HEIDELBERG-MOSCOW experiment in Gran-Sasso - yields evidence for the neutrinoless decay mode. This result is the first evidence for lepton number violation and proves the neutrino to be a Majorana particle. We give the present status of the analysis in these Proceedings. It excludes several of the neutrino mass scenarios allowed from present neutrino oscillation experiments - essentially only degenerate and partially degenerate mass scenarios survive. This result allows neutrinos to still play an important role as dark matter in the Universe. To improve the present result, considerably enlarged experiments are required, such as GENIUS. A GENIUS Test Facility has just been funded and will come into operation by end of 2002.

1 Introduction

Recently atmospheric and solar neutrino oscillation experiments have shown that neutrinos are massive. This was the first indication of beyond standard model physics. The absolute neutrino mass scale was, however, still unknown, and only neutrino oscillations and neutrinoless double beta decay together can solve this problem (see, e.g. [2,3,4]). Another question of fundamental importance is, that whether the neutrino is a Dirac or Majorana particle. Only double beta decay can solve this problem. Finally double beta decay has a unique sensitivity to probe lepton number conservation.

In this paper we will discuss the status of double beta decay search. We shall, in section 2, discuss the expectations for the observable of neutrinoless double beta decay, the effective neutrino mass \( \langle m_\nu \rangle \), from the most recent \( \nu \) oscillation experiments. In section 3 we shall discuss the recent evidence for the neutrinoless decay mode, and discuss the consequences for the neutrino mass scenarios which could be realized in nature. In section 4 we discuss the possible future potential of \( 0\nu \beta \beta \) experiments, which could improve the present accuracy.
2 Allowed Ranges of \( \langle m \rangle \) by \( \nu \) Oscillation Experiments

The observable of double beta decay
\[
\langle m \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| m_{ee}^{(1)} \right| + e^{i\phi_2} \left| m_{ee}^{(2)} \right| + e^{i\phi_3} \left| m_{ee}^{(3)} \right|
\]
with \( U_{ei} \) denoting elements of the neutrino mixing matrix, \( m_i \) neutrino mass eigenstates, and \( \phi_i \) relative Majorana CP phases, can be written in terms of oscillation parameters:

\[
\begin{align*}
|m_{ee}^{(1)}| &= |U_{e1}|^2 m_1, \\
|m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2}, \\
|m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}.
\end{align*}
\]

The effective mass \( \langle m \rangle \) is related with the half-life for 0\( \nu \)\( \beta \beta \) decay via
\[
\left( T_{1/2}^{0\nu} \right)^{-1} \sim \langle m \rangle^2,
\]
and for the limit on \( T_{1/2}^{0\nu} \) deducible in an experiment we have
\[
T_{1/2}^{0\nu} \sim a \sqrt{\frac{M}{\Delta E_B}}.
\]
Here \( a \) is the isotopical abundance of the \( \beta \beta \) emitter; \( M \) is the active detector mass; \( t \) is the measuring time; \( \Delta E \) is the energy resolution; \( B \) is the background count rate.

Neutrino oscillation experiments fix or restrict some of the parameters in (1)–(3), e.g. in the case of normal hierarchy solar neutrino experiments yield \( \Delta m_{21}^2, \) \( |U_{e1}|^2 = \cos^2 \theta_\odot \) and \( |U_{e2}|^2 = \sin^2 \theta_\odot \). Atmospheric neutrinos fix \( \Delta m_{32}^2, \) and experiments like CHOOZ, looking for \( \nu_e \) disappearance restrict \( |U_{e3}|^2 \). The phases \( \phi_i \) and the mass of the lightest neutrino, \( m_1 \) are free parameters. Double beta decay can fix the parameter \( m_1 \) and thus the absolute mass scale. The expectations for \( \langle m \rangle \) from oscillation experiments in different neutrino mass scenarios have been carefully analyzed in [2]. In sections 2.1 to 2.3 we give some examples.

---

Figure 1. Neutrino masses and mixings in the scheme with mass hierarchy. Coloured bars correspond to flavor admixtures in the mass eigenstates \( \nu_1, \nu_2, \nu_3 \). The quantity \( \langle m \rangle \) is determined by the dark blue bars denoting the admixture of the electron neutrino \( U_{e1} \).
Figure 2. Double beta decay observable $\langle m \rangle$ and oscillation parameters in the case of the MSW large mixing angle solution of the solar neutrino deficit, where the dominant contribution to $\langle m \rangle$ comes from the second state. Shown are lines of constant $\langle m \rangle$, the lowest line corresponding to $\langle m_{\nu} \rangle = 0.001$ eV, the upper line to 0.01 eV. The inner and outer closed line show the regions allowed by present solar neutrino experiments with 90% C.L. and 99% C.L., respectively. Double beta decay with sufficient sensitivity could check the LMA MSW solution. Complementary information could be obtained from the search for a day-night effect and spectral distortions in future solar neutrino experiments as well as a disappearance signal in KAMLAND [from 3].

2.1 Hierarchical Spectrum ($m_1 \ll m_2 \ll m_3$)

In hierarchical spectra (Fig. 1), motivated by analogies with the quark sector and the simplest see-saw models, the main contribution comes from $m_2$ or $m_3$. For the large mixing angle (LMA) MSW solution which is favored at present for the solar neutrino problem (see 20), the contribution of $m_2$ becomes dominant in the expression for $\langle m \rangle$, and

$$\langle m \rangle \simeq m_{ee}^{(2)} = \frac{\tan^2 \theta}{1 + \tan^2 \theta} \sqrt{\Delta m_{e\alpha}^2}.$$  

In the region allowed at 90% C.L. by Superkamiokande according to 21, the prediction for $\langle m \rangle$ becomes

$$\langle m \rangle = (1 \div 3) \cdot 10^{-3} \text{eV}.$$  

The prediction extends to $\langle m \rangle = 10^{-2}$ eV in the 99% C.L. range (Fig. 2).
2.2 Inverse Hierarchy \((m_3 \approx m_2 \gg m_1)\)

In inverse hierarchy scenarios (Fig. 3) the heaviest state with mass \(m_3\) is mainly the electron neutrino, its mass being determined by atmospheric neutrinos, \(m_3 \simeq \sqrt{\Delta m_{\text{atm}}^2}\). For the LMA MSW solution one finds \(\langle m \rangle = (1 \div 7) \cdot 10^{-2}\) eV.

2.3 Degenerate Spectrum \((m_1 \simeq m_2 \simeq m_3 \gtrsim 0.1\ eV)\)

In degenerate scenarios (Fig. 3) the contribution of \(m_3\) is strongly restricted by CHOOZ. The main contributions come from \(m_1\) and \(m_2\), depending on their admixture to the electron flavors, which is determined by the solar neutrino solution. We find

\[ m_{\text{min}} < \langle m \rangle < m_1 \quad \text{with} \quad \langle m_{\text{min}} \rangle = (\cos^2 \theta_\odot - \sin^2 \theta_\odot) m_1. \]  

This leads for the LMA solution to \(\langle m \rangle = (0.25 \div 1) \cdot m_1\), the allowed range corresponding to possible values of the unknown Majorana CP-phases.

After these examples we give a summary of our analysis of the \(\langle m \rangle\) allowed by \(\nu\) oscillation experiments for neutrino mass models in the presently

Figure 3. Left: Neutrino masses and mixing in the inverse hierarchy scenario. Right: Neutrino masses and mixings in the degenerate scheme.
favored scenarios, in Fig. 1. The size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases.

Figure 4. 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 recently observed value is given (95% c.l. range), and the best value. Framed parts of the bars: present status; not framed parts: expectation for running experiments; solid and dashed lines: experiments under construction or proposed, respectively. For references see 4, 5, 31, 49.

3 Evidence for the Neutrinoless Decay Mode

The status of present double beta experiments is shown in Fig. 3 and is extensively discussed in 4. The HEIDELBERG-MOSCOW experiment using the largest source strength of 11 kg of enriched $^{76}$Ge in form of five HP Ge-detectors is running since August 1990 in the Gran-Sasso underground laboratory and is since long time the most sensitive one. We communicate here the status of the analysis of November 2001.

3.1 Data from the HEIDELBERG-MOSCOW Experiment

The data taken in the period August 1990 - May 2000 (54.9813 kg y, or 723.44 mol-years are shown in Fig. 3. Also shown in Fig. 3. are the data of single site
events taken in the period November 1995 - May 2000 with our methods of pulse shape analysis (PSA). We have analysed those data with various statistical methods, in particular also with the Bayesian method (see, e.g.). This method is particularly suited for low counting rates, where the data follow a Poisson distribution, that cannot be approximated by a Gaussian.

Figure 5. HEIDELBERG-MOSCOW experiment. Left: energy spectrum in the range between 2000 keV and 2080 keV, after 54.9813 kgs. \( Q_{\beta\beta} = 2039.006(50) \) keV according to \( 11 \). Right: Spectrum of single site events (SSE) after 28.053 kgs, corrected for the efficiency of SSE identification. The accepted events have been identified as SSE events by all our three methods of pulse shape analysis. Shown are also the lines identified by the Bayesian method (see text).
Figures 6, 7 show the results of the analysis of the data with the Bayesian method. Shown is the probability $K$ to find a (Gaussian) line with known standard deviation of $\sigma = 1.70 \ (1.59) \text{ keV}$ corresponding to 4.00 (3.74), for 3.74 keV FWHM, as function of energy. This information was obtained by two-parametric Bayesian inference. We have asked for the intensity $I$ of a line at a given energy $E$ and for the background level. The background was assumed to be constant over the spectral range of 2000-2080 keV. For details of the procedure see 5. The probability $K$ is the ordinate in Figs. 6, 7.

This procedure reproduces $\gamma$-lines at the position of known weak lines from the decay of $^{214}\text{Bi}$ at 2010.7, 2016.7, 2021.8 and 2052.9 keV 13. In addition, a line centered at 2039 keV shows up. This is compatible with the Q-value of the double beta decay process. We emphasize, that at this energy no $\gamma$-line is expected according to the compilations in 13. The
background on the left-hand side identified by the Bayesian method is too high, because the procedure averages the background over all the spectrum (including lines), except the line it is trying to single out. Therefore, on the right side of Fig. 6 we show the same as on the left side, but in the spectral range of interest for double beta decay. Here the background is determined from a $\pm \sim 5\sigma$ energy interval, around $Q_{\beta\beta}$, where no lines are expected. The Bayesian analysis of this energy range yields a confidence level (i.e. the probability $K$) for a line to exist at $2039.0$ keV of $96.5\%$ c.l. ($2.1\sigma$). We repeated the analysis for the same data, but except detector 4, which had no muon shield and a slightly worse energy resolution ($46.502$ kg y). The result is similar to that given in Fig. 6, the probability we find for a line at $2039.0$ keV is $97.4\% (2.2\sigma)$.

We also applied the method recommended by the Particle Data Group. This method (which does not use the information that the line is Gaussian) finds a line at $2039$ keV on a confidence level of $3.1\sigma$ ($99.8\%$ c.l.).

The spectrum of single site events selects events confined to a few mm region in the detector corresponding to the track length of the emitted electrons - such as double beta events, and rejects multiple-site events - such as multiple Compton scattering events.

The expectation for a $0\nu\beta\beta$ signal would be a line of single site events on some background of multiple site events but also single site events, the latter coming e.g. from the continuum of the $2614$ keV $\gamma$-line from $^{208}$Tl (see, e.g., the simulation in [6]).

Installation of PSA has been performed in 1995 for the four large detectors. Detector Nr.5 runs since February 1995, detectors 2,3,4 since November 1995 with PSA. The measuring time with PSA from November 1995 until May 2000 is $36.532$ kg years, for detectors 2,3,5 it is $28.053$ kg y.

Fig. 5 shows the SSE spectrum obtained under the restriction that the signal simultaneously fulfills the criteria of all three methods for a single site event. Fig. 8 shows typical SSE and MSE events from our spectrum.

In total, we find 9 SSE events in the region $2034.1 - 2044.9$ keV ($\pm 3\sigma$ around $Q_{\beta\beta}$). Corrected for the efficiency to identify an SSE signal by successive application of all three PSA methods, which is $0.55 \pm 0.10$, we obtain a $0\nu\beta\beta$ signal of $(3.6 - 12.5)$ events with $68.3\%$ c.l. (best value 8.3 events). Analysis with the Bayesian method of the range $2000 - 2080$ keV shows again evidence for a line at the energy of $2039.0$ keV (Fig. 7). The analysis of the range $2032 - 2046$ keV yields a signal of single site events, as expected for neutrinoless double beta decay, with $96.8\%$ c.l. precisely at the $Q_{\beta\beta}$ value obtained in the precision experiment of [14] (Fig. 8). The PDG method gives a signal at $2039.0$ keV of $2.8\sigma$ ($99.4\%$).
Figure 8. Left: Shape of one candidate for $0\nu\beta\beta$ decay (energy 2038.61 keV) classified as SSE by all three methods of pulse shape discrimination. Right: Shape of one candidate (energy 2038.97 keV) classified as MSE by all three methods.

3.2 Half-Life and Effective Neutrino Mass

Under the assumption that the signal at $Q_{\beta\beta}$ is not produced by a background line of at present unknown origin, we can translate the observed number of events into half-lives. In Table 1 we give conservatively the values obtained with the Bayesian method. Also given are the effective neutrino masses $\langle m_\nu \rangle$ deduced using matrix elements from 34,12.

Table 1. Half-life for the neutrinoless decay mode and deduced effective neutrino mass from the HEIDELBERG-MOSCOW experiment.

| Significance [kg y] | Detectors | $T_{1/2}^{0\nu}$ y | $\langle m \rangle$ eV | Conf. level |
|--------------------|-----------|---------------------|-------------------|-------------|
| 54.9813            | 1,2,3,4,5 | (0.80 – 35.07) x 10^{25} | (0.08 - 0.54) | 95% c.l.  |
| 54.9813            | 1,2,3,4,5 | (1.04 – 3.46) x 10^{25}  | (0.26 - 0.47) | 68% c.l.  |
| 54.9813            | 1,2,3,4,5 | 1.61 x 10^{25}         | 0.38             | Best Value |
| 46.502             | 1,2,3,5  | (0.75 – 18.33) x 10^{25} | (0.11 - 0.56) | 95% c.l.  |
| 46.502             | 1,2,3,5  | (0.98 – 3.05) x 10^{25}  | (0.28 - 0.49) | 68% c.l.  |
| 46.502             | 1,2,3,5  | 1.50 x 10^{25}         | 0.39             | Best Value |
| 28.053             | 2,3,5 SSE| (0.88 – 22.38) x 10^{25} | (0.10 - 0.51) | 90% c.l.  |
| 28.053             | 2,3,5 SSE| (1.07 – 3.69) x 10^{25}  | (0.25 - 0.47) | 68% c.l.  |
| 28.053             | 2,3,5 SSE| 1.61 x 10^{25}         | 0.38             | Best Value |
We derive from the data taken with 46.502 kg y the half-life $T_{1/2}^{0\nu} = (0.8 - 18.3) \times 10^{25}$ y (95% c.l.). The analysis of the other data sets, shown in Table 1, and in particular of the single site events data, which play an important role in our conclusion, confirm this result.

The result obtained is consistent with the limits given earlier by the HEIDELBERG-MOSCOW experiment 1, considering that the background had been determined more conservatively there. It is also consistent with all other double beta experiments - which still reach less sensitivity. A second Ge-experiment, which has stopped operation in 1999 after reaching a significance of 9 kg y, yields (if one believes their method of ‘visual inspection’ in their data analysis), in a conservative analysis, a limit of $T_{1/2}^{0\nu} > 0.55 \times 10^{25}$ y (90% c.l.). The $^{128}Te$ geochemical experiment yields $\langle m_\nu \rangle < 1.1$ eV (68% c.l.), the $^{130}Te$ cryogenic experiment yields $\langle m_\nu \rangle < 1.8$ eV and the CdWO$_4$ experiment $\langle m_\nu \rangle < 2.6$ eV, all derived with the matrix elements of $\beta^2$ to make the results comparable to the present value (for references see 4).

Concluding we obtain, with about 95% probability, first evidence for the neutrinoless double beta decay mode. As a consequence, at this confidence level, lepton number is not conserved. Further the neutrino is a Majorana particle. The effective mass $\langle m \rangle$ is deduced to be $\langle m \rangle = (0.11 - 0.56)$ eV (95% c.l.), with best value of 0.39 eV. Allowing conservatively for an uncertainty of the nuclear matrix elements of $\pm 50\%$ (for detailed discussions of the status of nuclear matrix elements we refer to 12 and references therein) this range may widen to $\langle m \rangle = (0.05 - 0.84)$ eV (95% c.l.).

In this conclusion, it is assumed that contributions to $0\nu\beta\beta$ decay from processes other than the exchange of a Majorana neutrino (see, e.g. 4 and references therein) are negligible.

With the limit 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. 5) - allowing mainly only for degenerate and partially degenerate mass scenarios and an inverse hierarchy $3\nu$ - scenario (the latter being, however, strongly disfavored by a recent analysis of SN1987A. In particular hierarchical mass schemes are excluded at the present level of accuracy.

Assuming the degenerate scenarios to be realized in nature we fix - according to the formulae derived in 2 - the common mass eigenvalue of the degenerate neutrinos to $m = (0.05 - 3.4)$ eV. Part of the upper range is already excluded by tritium experiments, which give a limit of $m < 2.2$ eV (95% c.l.) 7. The full range can only partly (down to $\sim 0.5$ eV) be checked by future tritium decay experiments, but could be checked by some future $\beta\beta$
Figure 9. The impact of the evidence obtained for neutrinoless double beta decay in this paper (best value of the effective neutrino mass \( \langle m \rangle = 0.39 \text{ eV}, 95\% \text{ confidence range (0.05 - 0.84 eV) - allowing already for an uncertainty of the nuclear matrix element of a factor of } \pm 50\% ) \) 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 ) Hierarchical models are excluded by the new 0νββ decay result. Also 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.

Figure 10. Double beta decay observable \( \langle m \rangle \) and oscillation parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses \( m_0 \) and mixing \( \tan^2 \theta_{12} \). Also shown is a cosmological bound deduced from a fit of CMB and large scale structure and the expected sensitivity of the satellite experiments MAP and PLANCK. The present limit from tritium \( \beta \) decay of 2.2 eV would lie near the top of the figure. The range of \( \langle m \rangle \) fixed by the HEIDELBERG-MOSCOW experiment is, in the case of small solar neutrino mixing, already in the range to be explored by MAP and PLANCK.
experiments (see, e.g. next section). The deduced best value for the mass is consistent with expectations from experimental $\mu \to e\gamma$ 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 $^{24}$. 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 $^{25}$. The range of $\langle m \rangle$ fixed in this work, is, already now, in the range to be explored by the satellite experiments MAP and PLANCK $^{19}$ (see Fig. 10).

The neutrino mass deduced allows neutrinos to still play an important role as hot dark matter in the Universe.

4 Future of $\beta\beta$ Experiments

To improve the present sensitivity for the effective neutrino mass considerably, and to fix this quantity more accurately, requires new experimental approaches, as discussed extensively in $^{4,49,24,16,17,18}$. Some of them are indicated in Figs. 4,9.

It has been discussed earlier (see e.g. $^{4,49,24,16,17,18}24$), that of present generation experiments probably no one has a potential to probe $\langle m \rangle$ below the present HEIDELBERG-MOSCOW level (see Fig. 4).

The Milano cryogenic experiment using TeO$_2$ bolometers improved their values for the $\langle m \rangle$ from $\beta\beta$ decay of $^{130}$Te, from 5.3 eV in 1994 to 1.8 eV in 2000 $^{41}$. NEMO-III, originally aiming at a sensitivity of 0.1 eV, reduced their goals recently to $0.3 \div 0.7$ eV (see $^{44}$) (which is more consistent with estimates given by $^{43}$), to be reached in 6 years from starting of running, foreseen for the year 2002.

4.1 GENIUS and other Proposed Future Double Beta Experiments

With the era of the HEIDELBERG-MOSCOW experiment the time of the small smart experiments is over.

To reach significantly larger sensitivity, $\beta\beta$ experiments have to become large. On the other hand source strengths of up to 10 tons of enriched material touch the world production limits. This means that the background has to be reduced by the order a factor of 1000 and more compared to that of the HEIDELBERG-MOSCOW experiment.

Table 2 lists some key numbers for GENIUS, $^{16,17,24}$ which was the first proposal for a third generation double beta experiment, and of some other proposals made after the GENIUS proposal. The potential of some of them
Table 2. Some key numbers of future double beta decay experiments (and of the HEIDELBERG-MOSCOW experiment). Explanations: \(\nabla\) - assuming the background of the present pilot project. \(\ast\ast\) - with matrix element from \(34^{\text{Ge}}, 12^{\text{P}, 35^{\text{S}}, 36^{\text{S}}, 37^{\text{S} }}\) (see Table II in [24] and including an assumed uncertainty of \(\pm 50\%\) of the nuclear matrix element). \(\triangle\) - this case shown to demonstrate the ultimate limit of such experiments. For details see [4].

| \(\beta^\beta\)-Isotope | Name | Status | Mass (tonnes) | Assumed background \(\dagger\) events/kg y keV, \(\dagger\) events/kg y FWHM, \(*\) events/yFWHM | Running Time (tonn. years) | Results limit for \(0\nu\beta\beta\) half-life (years) | \(<m_\nu>\) (eV) |
|---------------------|------|--------|---------------|-------------------------------------------------|----------------|-----------------|----------------|
| \(76^{\text{Ge}}\)  | HEIDELBERG-MOSCOW | running since 1990 | 0.011 (enriched) | \(\dagger\) 0.06 \(\dagger\) 0.24 \(\ast\) 2 | 54.98 kgy | 0.8 - 18.3 x 10^{23} y 95\% c.l. | 0.05 - 0.84 eV \(\ast\ast\) |
| \(100^{\text{Mo}}\) | NEMO III | under constr. end 2001? | \(~0.01\) (enriched) | \(\dagger\) 0.0005 \(\dagger\) 0.2 \(\ast\) 2 | 50 kg y | 10^{24} | 0.3 - 0.7 |
| \(130^{\text{Te}}\) | CUORE | idea since 1998 | 0.75 (nat.) | \(\dagger\) 0.5 \(\dagger\) 4.5/1000 | 5 | 9 - 10^{24} | 0.2 - 0.5 |
| \(130^{\text{Te}}\) | CUORE | idea since 1998 | 0.75 (nat.) | \(\dagger\) 0.005 \(\dagger\) 0.045/45 | 5 | 9 - 10^{25} | 0.07 - 0.2 |
| \(100^{\text{Mo}}\) | MOON | idea since 1999 | 10 (enr.) | ? | 300 | ? | 0.03 |
| \(116^{\text{Cd}}\) | CAMEO | idea since 2000 | 0.65 (enr.) | \(\ast\) 3 | 3.1/5 - 8 | 10^{26} | 0.06 |
| \(136^{\text{Xe}}\) | EXO | Proposal since 1999 | 1 (enr.) | \(\ast\) 0.4 | 5 | 8.3 \times 10^{26} | 0.05 - 0.14 |
| \(76^{\text{Ge}}\)  | GENIUS | under constr. end 2001? | 11 kg (enr.) | \(\dagger\) 6 \times 10^{-3} | 3 | 1.6 \times 10^{26} | 0.15 |
| \(76^{\text{Ge}}\)  | GENIUS | Proposal since 1997 | 1 (enr.) | \(\dagger\) 0.04 \times 10^{-3} \(\ast\) 0.15/1.5 | 1 | 5.8 \times 10^{27} | 0.02 - 0.05 |
| \(76^{\text{Ge}}\)  | GENIUS | Proposal since 1997 | 10 (enr.) | \(\dagger\) 0.15 \times 10^{-3} \(\ast\) 6 | 10 | 2 \times 10^{28} | 0.01 - 0.028 |

is shown also in Fig. [3] and it is seen that not all of them will lead to large improvements in sensitivity. Among the latter is also the recently presented MAJORANA project [4], which does not really apply a striking new strategy for background reduction, particularly also after it was found that the projected segmentation of detectors may not work.
For more recent information on XMASS, EXO, MOON experiments see the contributions of Y. Suzuki, G. Gratta and H. Ejiri in Ref. 47. The CAMEO project in its now propagated variant GEM is nothing then a variant of GENIUS (see below) put into the BOREXINO tank, at some later time. CUORE has, with the complexity of cryogenic techniques, still to overcome serious problems of background to enter into interesting regions of $\langle m \rangle$. EXO needs still very extensive research and development to probe the applicability of the proposed detection method. In particular if it would be confirmed that tracks will be too short to be identified, it would act essentially only as a highly complicated calorimeter. In the GENIUS project a reduction by a factor of more than 1000 down to a background level of 0.1 events/tonne keV in the range of $0\nu\beta\beta$ decay is planned to be reached by removing all material close to the detectors, and by using naked Germanium detectors in a large tank of liquid nitrogen. It has been shown that the detectors show excellent performance under such conditions. For technical questions and extensive Monte Carlo simulations of the GENIUS project for its application in double beta decay we refer to.

| NEW PROJECTS | BACKGROUND REDUCTION | MASS INCREASE | POTENTIAL FOR DARK MATTER | POTENTIAL FOR SOLAR $\nu^\prime s$ |
|-------------|----------------------|--------------|--------------------------|----------------------|
| GENIUS      | +                    | +            | +                        | + *)                  |
| CUORE       | (+)                  | +            | -                        | -                    |
| MOON        | (+)                  | +            | -                        | -                    |
| EXO         | +                    | +            | -                        | +                    |
| MAJORANA    | -                    | +            | -                        | -                    |

*) real time measurement of pp neutrinos with threshold of 20 keV (!!!)

4.2 GENIUS and Other Beyond Standard Model Physics

GENIUS will allow besides the large increase in sensitivity for double beta decay described above, the access to a broad range of other beyond SM physics topics in the multi-TeV range. Already now $\beta\beta$ decay probes the TeV scale on which new physics should manifest itself (see, e.g. 16, 29, 30). Basing to a large extent on the theoretical work of the Heidelberg group in the last six years, the HEIDELBERG-MOSCOW experiment yields results for SUSY models (R-parity breaking, neutrino mass), leptoquarks (leptoquarks-Higgs coupling), compositeness, right-handed $W$ mass, nonconservation of Lorentz
invariance and equivalence principle, mass of a heavy left or righthanded neutrino, competitive to corresponding results from high-energy accelerators like TEVATRON and HERA. The potential of GENIUS extends into the multi-TeV region for these fields and its sensitivity would correspond to that of LHC or NLC and beyond (for details see [4,29,30]).

4.3 GENIUS-Test Facility

Construction of a test facility for GENIUS – GENIUS-TF – consisting of ~ 40 kg of HP Ge detectors suspended in a liquid nitrogen box has been started. Up to summer of 2001, six detectors each of ~ 2.5 kg and with a threshold of as low as ~ 500 eV have been produced.

Besides test of various parameters of the GENIUS project, the test facility would allow, with the projected background of 2-4 events/(kg·y·keV) in the low-energy range, to probe the DAMA evidence for dark matter by the seasonal modulation signature, (see [32,33]).

5 Conclusion

The status of present double beta decay search has been discussed, and recent evidence for a non-vanishing Majorana neutrino mass obtained by the HEIDELBERG-MOSCOW experiment has been presented. Future projects to improve the present accuracy of the effective neutrino mass have been discussed. The most sensitive of them and perhaps at the same time most realistic one, is the GENIUS project. GENIUS is the only of the new projects (see also Table 3) which simultaneously has a huge potential for cold dark matter search, and for real-time detection of low-energy neutrinos (see [24,26,30,47,49]).

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