

GENIUS -
a New Experiment with Large
Discovery Potential for Particle and
Astrophysics

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Abstract

The recent results from the HEIDELBERG–MOSCOW experiment have demonstrated the large potential of double beta decay to search for new physics beyond the Standard Model. To increase by a major step the present sensitivity for double beta decay and dark matter search much bigger source strengths and a much lower background are needed than used in experiments under operation at present or under construction. We describe here a project which would operate one ton of 'naked' enriched GERmanium-detectors in liquid NITrogen as shielding in an Underground Setup (GENIUS). It improves the sensitivity to neutrino masses to 0.01 eV. A ten ton version would probe neutrino masses even down to 10^{-3} eV. The first version would allow to test the atmospheric neutrino problem, the second at least part of the solar neutrino problem. Both versions would allow in addition significant contributions to testing several classes of GUT models. These are especially tests of R-parity breaking and conserving supersymmetry models - including sneutrino masses -, leptoquark masses and mechanism and right-handed W-boson masses comparable to LHC. The second issue of the experiment is the search for dark matter in the universe. The full MSSM parameter space for prediction of neutralinos as dark matter particles could be covered already in a first step of the full experiment using only 100 kg of ^{76}Ge or even of natural Ge making the experiment competitive to LHC in the search for supersymmetry.

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1 Introduction

Searches for rare events, nuclear double beta decay [1, 2], and nuclear recoils from elastically scattered weak interacting massive particles (WIMPS) [3, 4, 5, 6] are performed to discover new particles and test new particle physics theories [7, 8]. This type of experiments is in contest to high energy accelerator experiments in the investigation of physics at very high energies. Two topics are of greatest interest in high energy physics and in astrophysics. Test of the existence of a so called SUpersYmmetry (SUSY) is one, if not the, major aim of the Large Hadron Collider (LHC) [9, 10, 11], which will dominate the high energy physics research in the next decade. Second, dark matter, which manifests itself by its gravitational force, puzzles astrophysicists since a long time [3, 4, 5, 6]. A very close connection between both issues in addition to SUSY which could be responsible for the cold dark matter (neutralinos), could be established by non zero neutrino masses as candidates for hot dark matter, and especially degenerate neutrino mass scenarios [12, 13, 14] can explain the recent observations by the COBE satellite for dark matter [15, 16]. Our new GERmanium in NITrogen Underground Setup (GENIUS), first proposed and presented by [1], and described in detail also in [17, 18], is an experiment which is optimized to address both issues. It is a large step beyond the HEIDELBERG-MOSCOW-Experiment [19], which is the most sensitive existing double beta decay experiment at present and for the next years and which has also given the most stringent limits on WIMPS for several years [20]. The GENIUS project, which we describe in this paper, would allow a large step forward in sensitivity and could represent the future of this field. It would not only be unique in probing *absolutely* the neutrino mass down to 10^{-2} or 10^{-3} eV (all running neutrino oscillation experiments probe only *differences* of masses!) but would also be more sensitive than all accelerator neutrino oscillation experiments running at present or being under construction for the future. It could further decisively contribute to the solution of the atmospheric and solar neutrino problems.

We will show that measuring neutrino masses as small as (few) $\times 10^{-3}$ eV puts double beta decay in a position to test various hypothesizes about the neutrino mass spectrum which have been put forward to explain the puzzling existing data from neutrino oscillation experiments. For example, a negative search for $0\nu\beta\beta$ decay by GENIUS would rule out degenerate neutrino mass scenarios unless neutrinos are maximally mixed and have different relative signs in their CP-phases at the same time.¹ The impact of GENIUS on neutrino mass models is discussed in sections 3.1-3.2.

Besides light neutrinos, neutrinoless double beta decay can occur via several

¹Since oscillation experiments measure only differences of squared masses the absolute mass scale can not be fixed by these experiments. GENIUS is the only proposed experiment which could probe *masses* in the meV range up to now. However, recall the $0\nu\beta\beta$ decay measures *Majorana* neutrino masses only.

other mechanisms, such as for example heavy right-handed neutrino exchange in left-right symmetric models [21, 22], by the exchange of gluinos, squarks, etc. in R-parity violating [23, 24, 25] and exchange of e.g. sneutrinos in R-parity conserving supersymmetry [26, 27], as well as via leptoquark exchange [28]. The impact of GENIUS on these models is also discussed and compared to other future experiments in section 3.3.

Its ultra-low background allows GENIUS to act also as a very efficient dark matter detector. It would allow, for the first time ever, to cover the complete MSSM neutralino parameter space. GENIUS thus should either confirm or rule out the present favorite particle physics candidate for CDM, the neutralino, and test the hypothesis of R-parity conservation to unanticipated levels, as discussed in section 3.4.

The costs of the experiment would be a minor fraction of those of detectors prepared for LHC physics as CMS or ATLAS, or close to those of the long baseline ν -oscillation experiments under construction, like MINOS at Fermilab or just like the beam dump (!) of the CERN \rightarrow Gran Sasso ν oscillation experiment. The infrastructure and space required by the experiment in an underground laboratory could be provided by the INFN in the Gran Sasso Laboratory in Italy.

1.1 $\beta\beta$ -Decay Searches

Nuclear double beta decay can be observed, if the single beta decay is either energetically forbidden or through high angular momentum differences between final and initial nucleus suppressed. The decay is divided into two major modes, according to the number of emitted particles.

$$2\nu\beta\beta \quad {}^Z_A X \quad \rightarrow \quad {}^{Z+2}_A X + 2e^- + 2\bar{\nu}_e \quad (1)$$

$$0\nu\beta\beta \quad {}^Z_A X \quad \rightarrow \quad {}^{Z+2}_A X + 2e^- \quad (2)$$

The two neutrino $2\nu\beta\beta$ mode occurs under emission of two electrons and two antineutrinos, whereas in case of the neutrinoless $0\nu\beta\beta$ mode only two electrons are emitted. The $2\nu\beta\beta$ mode is allowed in the standard model of particle physics and is already observed for 10 isotopes. The by far more interesting decay mode is the $0\nu\beta\beta$ mode, whose observation implies the existence of new physics beyond the standard model. For possible mechanisms, aside from the Majorana neutrino exchange, leading to this decay see [1, 2, 21, 22, 23, 24, 25, 26, 27, 28].

The best presently existing limits for $0\nu\beta\beta$ -decay half-lives and the deduced neutrino masses are plotted in figure 1 and 2: ${}^{48}\text{Ca}$ [29], ${}^{76}\text{Ge}$ [19], ${}^{82}\text{Se}$ [30], ${}^{100}\text{Mo}$ [31], ${}^{116}\text{Cd}$ [32], ${}^{130}\text{Te}$ [33], ${}^{136}\text{Xe}$ [34] and ${}^{150}\text{Nd}$ [35]. These setups and extensions of them (see [37] for the Gotthard ${}^{136}\text{Xe}$ TPC experiment, [33, 87] for the ${}^{130}\text{Te}$ cryogenic experiment, [36, 88] for NEMO) or new experiments under construction like a new ELEGANT with ${}^{48}\text{Ca}$ [38] or in planning like KAMLAND (using big

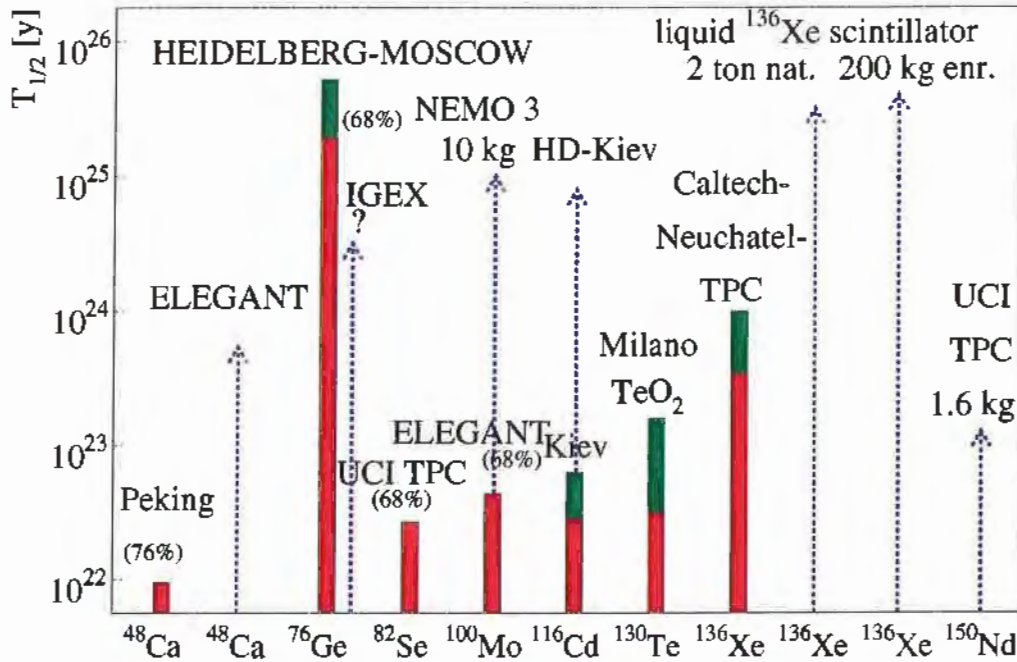


Figure 1: Present half life limits (red bars), 1997, and 'safe' expectations (green bars) for the near future (until the year 2000) and long term planned or hypothetical experiments (dashed lines) for the further future of the most promising $\beta\beta$ -experiments.

amounts of ^{136}Xe in scintillators in KAMIOKA) [89, 90], etc., will not reach or exceed the limit reachable with ^{76}Ge (HEIDELBERG-MOSCOW experiment) of 0.1 - 0.2 eV [19, 1]. For example a limit of 0.3 eV - almost the limit reached now by the HEIDELBERG-MOSCOW-Experiment- is scheduled for the NEMO experiment for the year 2004. The ^{48}Ca experiment of the Osaka group plans to reach a limit of 0.8 eV [39], just to mention the two perhaps most promising experiments behind the HEIDELBERG-MOSCOW-Experiment, which aims to a limit of 0.1 - 0.2 eV in the year 2000. KAMLAND whose realization is still *very* far from now, could reach 0.2 eV [89]. So 0.1 eV is the definite limit for all presently existing or planned $\beta\beta$ experiments (see also [40]). Therefore the GENIUS experiment would be a step into a totally new half life and neutrino mass region, which is not accessible by any other double beta decay experiment.

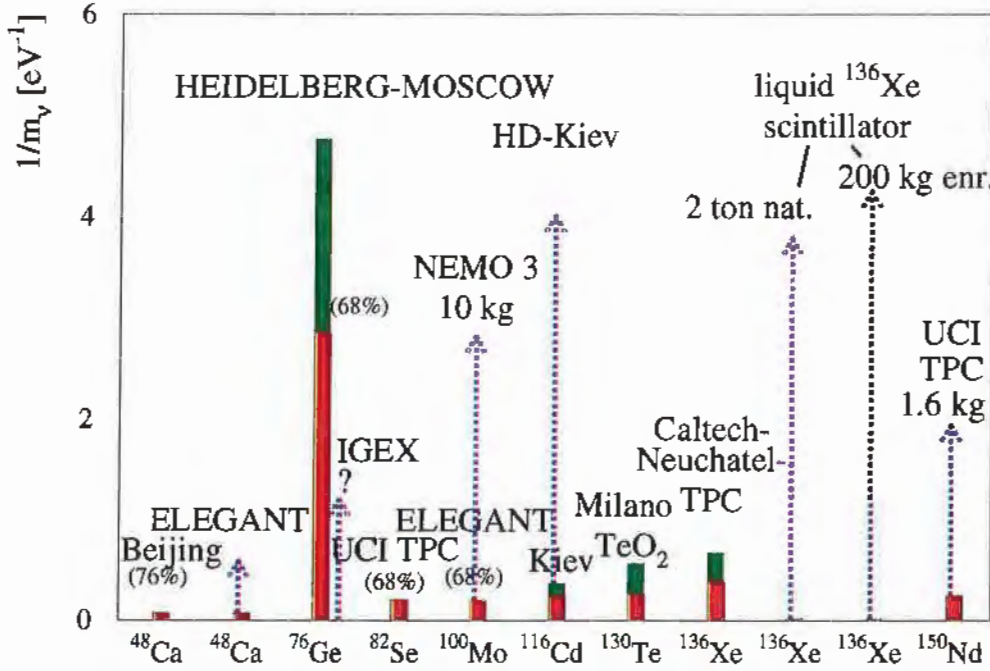


Figure 2: Inverse neutrino mass limits from the neutrinoless double decay half life limits of figure 1. Present limits (red bars), and ‘safe’ expectations (green bars) for the near future (until the year 2000) and long term planned or hypothetical experiments (dashed lines) for the further future of the most promising $\beta\beta$ -experiments.

1.2 Currently Existing Experimental Data on Neutrino Masses

1.2.1 Upper Limits on Neutrino Masses

The most model-independent measurements of neutrino masses come from kinematic searches. The particle data group [41] currently quotes the following limits:

$$m_{\nu_e} \leq 15 \text{ eV}, \quad (3)$$

$$m_{\nu_\mu} \leq 170 \text{ keV}, \quad (4)$$

$$m_{\nu_\tau} \leq 23 \text{ MeV}. \quad (5)$$

In addition, there is the constraint on the effective Majorana neutrino mass from the Heidelberg-Moscow double beta decay experiment, which claims [1, 19]:

$$\langle m_\nu \rangle \leq 0.5 \text{ eV} \quad (6)$$

1.2.2 Hints on Finite Neutrino Masses

More interesting than limits may be the existing hints on finite neutrino masses. One should keep in mind, however, that these are only hints: Not a single positive measurement of neutrino masses is currently firmly accepted.

At present there are four independent indications of finite neutrino masses. These are *i*) the solar neutrino problem [42], *ii*) the atmospheric neutrino problem [43], *iii*) the LSND measurement [44, 45] and *iv*) neutrinos as candidates for the hot dark matter [15, 16].

The first three are oscillation experiments and, therefore, by themselves give *no information about absolute values of neutrino masses*. It is important to note that only the assumption of neutrinos being the hot dark matter fixes the overall scale of neutrino masses. Recall that for neutrinos being interesting candidates for the hot dark matter, at least one neutrino should have a mass in the (few) eV range.

The solar neutrino problem can be explained by the disappearance of electron neutrinos. Since no appearance experiment exists for solar neutrinos the electron neutrinos can oscillate into any flavor: μ or τ neutrinos, or even new, sterile neutrinos. As is well-known, there are three solutions to the solar neutrino problem in terms of neutrino parameters. There are two MSW solutions;² the small-angle solution with $\Delta m^2 \approx (5 \times 10^{-6} - 1 \times 10^{-5}) \text{ eV}^2$ and $\sin^2 2\theta \approx (\text{few}) 10^{-3}$, and the large-angle solution with $\Delta m^2 \approx 10^{-(4-5)} \text{ eV}^2$ and $\sin^2 2\theta \approx (\text{few}) 10^{-1}$. In addition there is the so-called “just-so” solution of vacuum oscillations with parameters $\Delta m^2 \approx 10^{-(10-11)}$ and $\sin^2 2\theta \geq 0.5$. These values are valid assuming a two-flavor oscillation scheme only. In reality the situation is more complex. For a quasi three-generation analysis see, for example, the work of Fogli et al. [46]. Note, however, that also [46] does not deal with a *complete* three-generation analysis. Instead, ref. [46] assumes arbitrarily that the neutrino masses follow either a partially degenerate pattern or are strongly hierarchical.

The atmospheric neutrino problem, on the other hand, could be explained either by the appearance of electron neutrinos or the disappearance of muon neutrinos, i.e. one can either have $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_{\tau,s}$. In terms of Δm^2 and $\sin^2 2\theta$ both hypotheses require similar values: $\Delta m^2 \approx 0.1 \text{ eV}^2$ and $\sin^2 2\theta \geq 0.3$.

The LSND [44] measurement directly searches for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. An observed excess of $\bar{\nu}_e$ events has been interpreted by the LSND collaboration as evidence for oscillations with an oscillation probability of approximately $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \simeq (0.31 \pm 0.12 \pm 0.05) \%$. The LSND collaboration has also searched for $\nu_\mu \rightarrow \nu_e$ oscillations and obtained recently $P_{\nu_\mu \rightarrow \nu_e} \simeq (0.26 \pm 0.10 \pm 0.05) \%$. [45], which has been taken as an independent check for the existence of neutrino oscillations.

If neutrinos constitute the hot dark matter in the universe, at least one flavor

²It is very interesting to note, that the mass ranges of the solar neutrino solutions are fixed by the chlorine data alone. Taking only the Kamiokande and gallium data one can explain the solar neutrino problem for practically *any* Δm^2 .

should have a mass of the order of $m_\nu \approx (\text{few}) \text{ eV}$ [15, 16]. Masses below the eV scale would render neutrinos cosmologically uninteresting.

Mainly due to these four indications in the past few years a huge number of neutrino mass models have been constructed. A recent review can be found in [47].

1.3 Direct Dark Matter Detection

The existence of a so called Dark Matter which does not emit detectable amounts of electromagnetic radiation is established through the observation of the galaxy rotation curves [48]. In most galaxies the radial velocity distribution does not decrease as expected from the amount of visible matter. Instead the rotation curves are usually flat up to the largest observable distances. This observation strongly indicates the existence of dark matter in the galaxies. During the last years at least part of this dark matter has been discovered in form of Massive Compact Halo Objects (MACHO). These MACHOs consist of ordinary matter like stars and planets and belong to the group of baryonic dark matter. Recently the experiments MACHO, EROS and OGLE started to observe MACHOs by searching for the light amplification of distant stars. Such a microlensing effect occurs, if the line of site to the distant star is passed by the MACHO. Analysis of the first years of data taken in direction to the large Magellanic cloud by the MACHO collaboration leads to the conclusion, that only 50 % of the dark matter halo in a standard spherical halo model can be made up by MACHOs [49, 50]. The most probable MACHO mass of 0.5 solar mass contradicts direct observation of halo objects and has to be clarified [49]. Besides these MACHOs another source of dark matter in the Milky Way is still required.

Further indication for dark matter in the universe comes from observation of more distant objects. The gravitational potentials of clusters of galaxies, which are observed by X-ray emitting gas [51], the galaxy velocity distributions and the gravitational lensing of distant objects, indicate that the masses of the clusters are bigger than that of the sum of the observable visible objects. In addition there are theoretical reasons to believe in the existence of dark matter. Especially, the popular inflation models need usually the mass density to be critical.

Then, the Big Bang nucleosynthesis theory, which predicts the correct amount of light elements in the universe, suggests, that the fraction of baryonic dark matter is at most 10 % of the total mass in the universe, thus leaving 90 % for non baryonic dark matter [52]. Non-baryonic dark matter is also needed to explain the observed cosmic microwave background fluctuations. The structure formation models, which fit best the observations, consist of a mixture of hot and cold dark matter. The cold dark matter may be divided into two classes of candidates: axions and Weakly interacting massive particles (WIMPs) (see e. g. [53, 8]).

Since the WIMPs interact with normal matter not only by the gravitational

force, but also by a coupling with similar cross sections like the weak interaction, observation of such events should be possible. For a mean WIMP velocity of $10^{-3}c$ nuclear recoils below 100 keV from GeV/c^2 particles are expected.

The favorite WIMP candidate is the lightest supersymmetric particle (LSP) in the minimal supersymmetric standard model (MSSM). Assuming a local WIMP halo density of $0.3 - 0.7 \text{ GeV}/\text{cm}^3$ the expected detection rates for this particle are below 1 per day and kg detector mass [54, 55, 5] which cannot be reached by any experiment at present due to background from sources such as natural radioactivity, neutrons or nuclear beta decay. Therefore only limits on the WIMP–nucleon cross section as a function of the WIMP mass are deduced. The GENIUS experiment will be the only one, which could seriously test the MSSM predictions over the whole SUSY parameter space (see sections 2.4, 2.5 and 3.4).

2 The GENIUS Experiment

The idea of the GENIUS project is to operate a large amount of 'naked' enriched Ge-detectors in a liquid shielding of very low-level radioactive material. From the HEIDELBERG-MOSCOW-Experiment we learned that the main contributions to the background spectrum arise from the cryostat system and the lead shielding. A substantial progress by using cleaner materials cannot be expected, without reducing the background in the materials next to the detectors. The possibility to measure at much lower radioactivity levels is demonstrated by the new solar neutrino experiments Super Kamiokande[56], SNO[57] and Borexino[58]. A very promising way for operation of HPGe-detectors would be to put them into a liquid, which cools them to their working temperature and shields them from external radioactivity (see Fig. 3). The idea to operate Ge detectors in liquid nitrogen has been already mentioned earlier [59].

2.1 The Gran Sasso Laboratory

The Gran Sasso Laboratory is situated under the Gran Sasso mountain about 100 km east of Rome in Italy. The laboratory was built together with a 11 km long motorway tunnel. It consists of three large halls with 1.400 m rock overburden providing a shielding from the cosmic rays equivalent to 3.600 m of water. The outside buildings of the laboratory contain the required infrastructure to run the experiments. The first generation of experiments, in operation since the end of the eighties, includes the solar neutrino detector GALLEX, a magnetic monopole search by MACRO, supernova neutrino detection by LVD and several smaller experiments like the HEIDELBERG-MOSCOW experiment.

The shielding provided by the Gran Sasso laboratory would be sufficient for the GENIUS experiment and the space requirements of the liquid nitrogen tank could be fulfilled without further excavations. The safety requirements for the underground storage of large amounts of liquid gas were already investigated for the ICARUS experiment, which would use several kton of liquid argon. The easy access and the very good infrastructure of the laboratory make it first choice for the GENIUS experiment.

2.2 The Shielding

Table 1 gives some properties of nitrogen, argon and xenon. All three liquids can be processed to very high purity. The advantages of nitrogen are its low price and low temperature. The drawback of a liquid nitrogen shielding is its low density, which requires a very large setup to achieve sufficient shielding from external activities. Liquid argon shields better by a factor of two, but contains the β -emitter ^{39}Ar with 279 years half life, which is produced through $^{38}\text{Ar}(n,\gamma)$. The Q-value of 565 keV is well below the Q-value of the ^{76}Ge double beta decay,

Table 1: Properties of the liquids nitrogen, argon and xenon.

Liquid	Melting point [K]	Boiling point [K]	Density [g/cm ³] ^a
nitrogen	63	77	0.80
argon	83	87	1.63
xenon	161	165	3.52

^aDensity at normal pressure and boiling temperature, except argon density at 81.7 K.

but the electrons would contribute to the background in the dark matter recoil energy region. Liquid xenon has a higher density, but its temperature is at the upper edge for the operation of HPGe-detectors and the price is an additional problem. Altogether, the best choice for a liquid shielding would be nitrogen.

A nitrogen tank could be designed in two approaches to achieve lowest background. One possibility would be to use selected low activity materials for the tank wall and an additional shielding against radioactivity from outside. The second possibility would be to use a standard design made of standard materials for dewar production. In this case the diameter of the tank has to be big enough to shield all activities from outside and from the tank walls. The advantages of the first approach are a smaller detector size with reduced material usage. But the necessity to use selected materials and additional shieldings would probably lead to higher costs, than in case of the second approach. In the following we concentrate on the second approach.

2.3 The Germanium Detectors Inside the Liquid Shielding

To demonstrate the possibility to operate Germanium detectors inside liquid nitrogen we used a p-type HPGe-detector. Figure 4 shows the spectrum measured with the detector inside a 50 l dewar. The dewar was surrounded by 10 cm lead. The FET was mounted on a small board inside the nitrogen 6 cm above the crystal and connected with 1 m long HV and signal cables to the preamplifier (see figure 5).

The energy resolution (FWHM) was measured with a ¹³³Ba source at 81.0 keV to be 1.21 ± 0.01 keV and at 356 keV to be 1.51 ± 0.01 keV. With a ⁶⁰Co source 1.95 keV were measured at 1332 keV. The resolution is only about 0.1 keV worse than in a standard cryostat, most probably due to a non polished gold foil used as signal contact. Note, that the TPI, a measure for the leakage current, changed only by one % between HV off and 4000 V. Figure 6 shows the spectrum measured with a ¹³³Ba source. The lead X-rays and an energy threshold below 10 keV can also be seen.

A point, which should receive some attention for the GENIUS experiment,

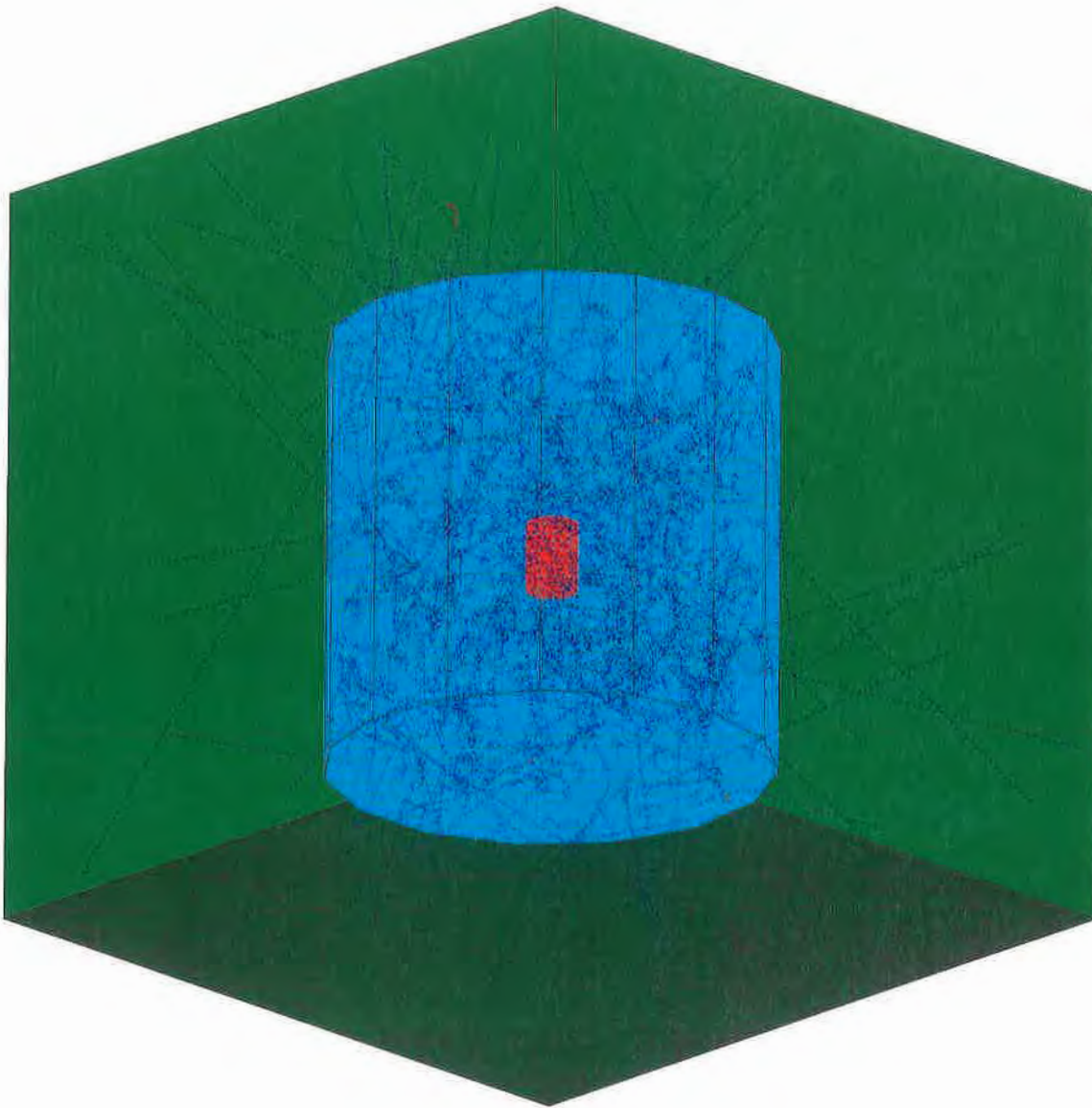


Figure 3: Simplified model of the GENIUS experiment: 288 enriched ^{76}Ge detectors (red) with a total of one ton mass in the center of a 9 m high liquid nitrogen (light blue) tank with 9 m diameter; GEANT Monte Carlo simulation of 1000 randomly distributed 2.6 MeV photons (dark blue lines) in the nitrogen is also shown.

might be electrical interference of several detectors, which has to be tested. From the point of view of lowest radioactive level the production and transportation of the detectors at the Earth's surface have to be reconsidered. Already in the HEIDELBERG-MOSCOW-Experiment lines from cosmogenic activities *inside* the

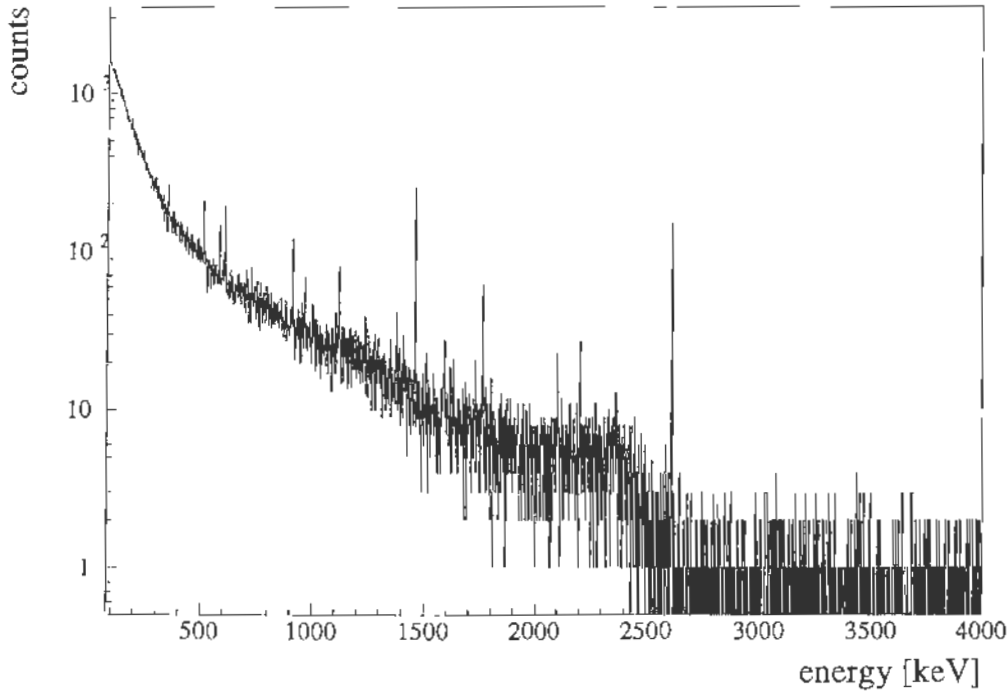


Figure 4: Spectrum of a HPGe-detector operated in liquid nitrogen in the Heidelberg underground site; lines of natural radioactivity and muon induced background above 3 MeV can be seen.

detectors could be identified. Production of the detectors inside the underground laboratory is probably the most straightforward way to avoid the cosmogenic activation at the level of background aimed at.

Muon induced background contributes about 10 % to the spectrum in the 2 MeV region of the HEIDELBERG-MOSCOW-Experiment. This would mean, however, a large contribution to the background in the GENIUS experiment. This background could be suppressed by using an active shielding either enclosing the nitrogen tank or by using scintillation light from the nitrogen itself. Since pure nitrogen does not scintillate it has to be doped with some substance. However, our simulations show, that an anticoincidence of the 288 detectors reduces the count rate of muon induced events sufficiently.

Neutron induced background has been proved to exist in the HEIDELBERG-MOSCOW-Experiment by subtracting data accumulated with neutron shield from the data accumulated without neutron shielding. However, this background cannot be compared directly to that of the nitrogen environment in the GENIUS experiment leading to different effects to those from the lead and copper shielding. The low mass of nitrogen would thermalize the neutrons. Additionally there is for example the prominent $^{14}\text{N}(n,p)^{14}\text{C}$ reaction which would contribute (^{14}C

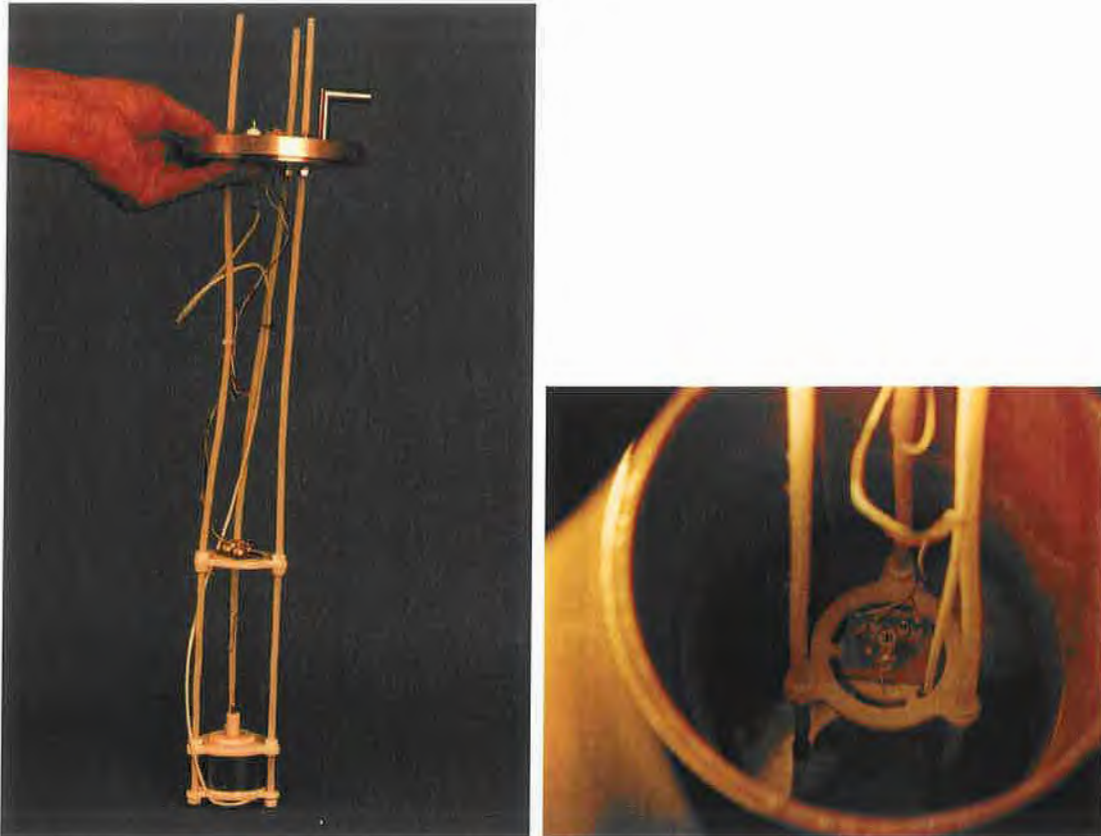


Figure 5: Setup for operation of one 'naked' Germanium detector in liquid nitrogen: frame with FET platform and crystal (left) and view into the liquid nitrogen dewar (right).

is a β^- -emitter with $Q=156.5$ keV) [60]. For the application of GENIUS for low energy measurements like WIMP direct detection one has to take care of the intrinsic, cosmogenically produced low energy background, which is irrelevant for double beta decay measurements.

The requirements for the data acquisition are:

- high energy resolution in the energy range from 10 keV to 2 MeV
- event by event data acquisition
- separated energy information of each detector

Calibration of the experiment could be done by introducing sealed sources into the nitrogen tank. Positioning of one or more sources in the middle of the germanium detectors would allow to get a good energy calibration for the experiment. A calibration in the low energy range would be particularly easy, since the unshielded detectors would be sensitive to very low energy gamma rays.

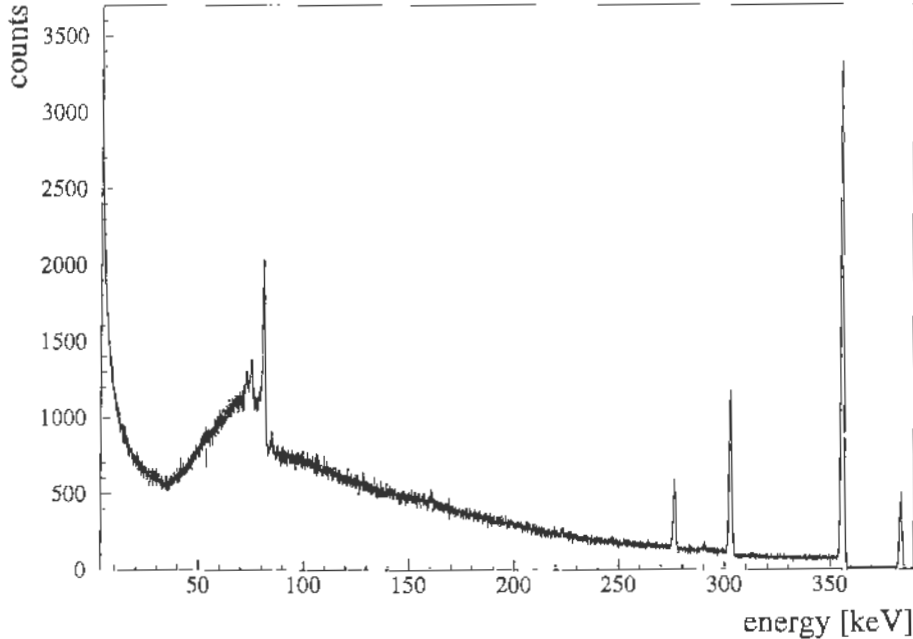


Figure 6: Spectrum of a ^{133}Ba source measured with a HPGe-detector operated in liquid nitrogen in the Heidelberg low-level laboratory. X-rays from lead can be seen with energies of 72.8 keV and 75.0 keV.

2.4 Expected performance

To determine the size of the experiment and the required purity levels we used the Monte Carlo code GEANT extended for the simulation of radioactive decays. This version was already successfully employed in the measurement of the $2\nu\beta\beta$ half life and the investigation of background in the HEIDELBERG-MOSCOW-Experiment[19].

The sources of radioactive background in the GENIUS experiment are differentiated according to their origin. The external background arise from γ -fluxes and neutrons from the natural activities in the surrounding rock. The muon induced background is not negligible in spite of six orders of magnitude reduction through the Gran Sasso mountain. Internal background is expected from impurities in the vessel, the liquid nitrogen and the crystals themselves.

2.4.1 Signal rates

The signal of the $1.77 \cdot 10^{21}\text{y}$ half life $2\nu\beta\beta$ decay is the dominating feature of the GENIUS energy spectrum (see figure 7). After one year of measurement the $2\nu\beta\beta$ spectrum contains $4 \cdot 10^5$ events. But only 0.3 events per year are expected from the neutrinoless double beta decay, assuming the neutrino to have a mass

Table 2: Required purity levels for the liquid nitrogen.

Isotope	Activity	Decays/year
^{222}Rn	0.05 mBq/m ³	8·10 ⁵
^{238}U (4n+2 series)	1·10 ⁻¹⁵ g/g	2·10 ⁵
^{232}Th (4n series)	5·10 ⁻¹⁵ g/g	3·10 ⁵
^{40}K	1·10 ⁻¹⁵ g/g	4·10 ⁶

of 10⁻²eV, which corresponds to the ultimate sensitivity of the 1 ton experiment. The expected neutralino rates range from 10 to 10⁵ counts/keV·t·y. The design goal for the detector is to have the sensitivity to test 0.3 events in the 2 MeV and 10 events in the 30 keV region. Since in the low energy region the simulated $2\nu\beta\beta$ spectrum contains by a factor of 10 more events, the $2\nu\beta\beta$ spectrum has to be subtracted. Another promising way would be to exploit the seasonal modulation of the dark matter flux [61]. Note, that the $0\nu\beta\beta$ measurement is not affected by the $2\nu\beta\beta$ signal (which is a major source of background in other experiments such as e. g. NEMO). This is a result of the very good energy resolution of the Ge detectors.

2.4.2 Estimate of background

The background is estimated using a simplified model of the GENIUS experiment. It consists of 288 Ge-detectors of 3.6 kg each, arranged in six radial symmetric layers of 48 detectors. The detectors occupy 1 m height and 1 m in diameter in the center of a tank, which is 9 m in height and 9 m in diameter and filled with liquid nitrogen. The vessel is made of 2 cm thick steel. The setup can be seen in figure 3 together with a simulation of 1000 2615 keV photons randomly distributed inside the nitrogen.

2.4.3 Activities in the nitrogen

The main contributions of radioactivities inside the nitrogen are expected from the nuclear decay chains of U/Ra with decays of ^{234}Th , ^{234}U , ^{230}Th , ^{226}Ra , ^{214}Pb , ^{214}Bi and ^{210}Pb , U/Th with decays of ^{228}Ac , ^{228}Th , ^{224}Ra , ^{212}Pb , ^{212}Bi and ^{208}Tl , primordial ^{40}K and ^{222}Rn . To study the required purity levels we simulated 28 million decays of each isotope randomly distributed inside the nitrogen. The spectra of the different isotopes in the decay chains are summed under the assumption that the chains are in equilibrium. The energy spectra of non-coincident events are shown in figure 7 assuming purity levels as listed in table 2. All requirements except for the ^{222}Rn contamination are less stringent, than those which are already achieved in the Counting Test Facility (CTF) for the Borexino experiment. The sum of all non-coincident events is plotted with a thick line and of all events with a dashed line in figure 7. The reduction through anticoincidence is about

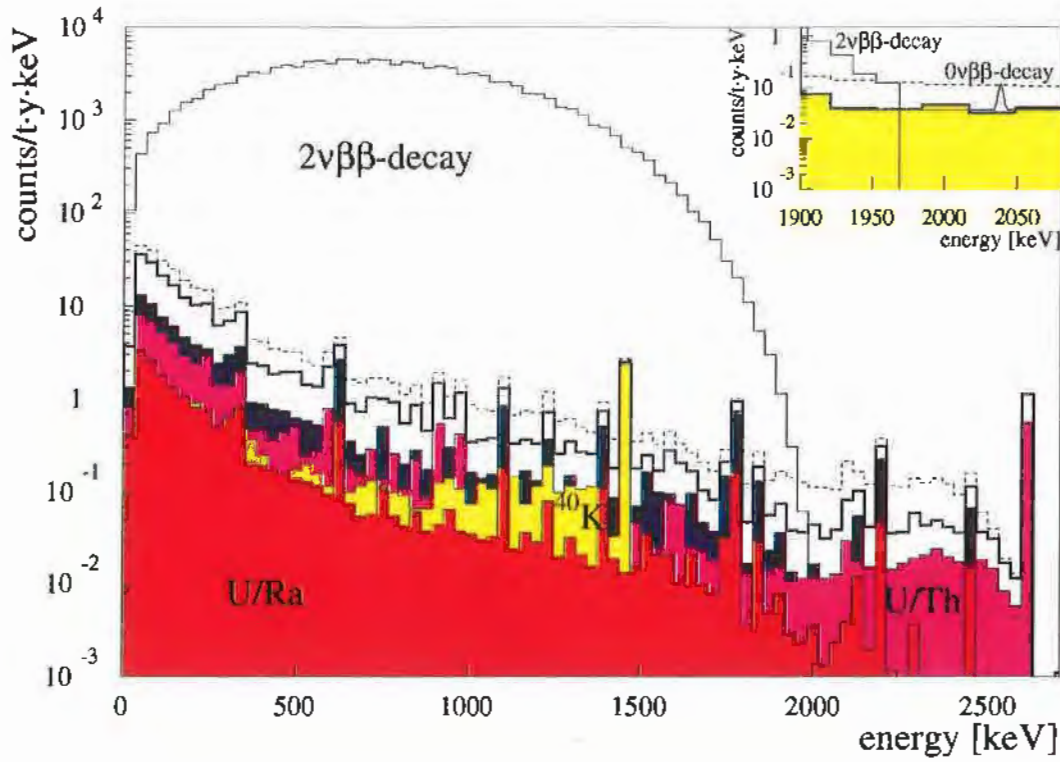


Figure 7: Monte Carlo simulation of U/Ra (red), U/Th (pink) and ^{40}K (yellow), ^{222}Rn (blue) activities in the liquid nitrogen; the sum of the activities is shown with anticoincidence between the 288 detectors (thick line and yellow in the inserted histogram) and without (dashed line); the $2\nu\beta\beta$ -decay dominates the spectrum with 4 million events per year; the impurity levels are assumed as given in table 2.

a factor of 10. The counting rate in the region of interest for the neutrinoless double beta decay is 0.04 counts/keV \cdot y \cdot t. Below 100 keV the counting rate is about 10 counts/keV \cdot y \cdot t.

2.4.4 Activities in the vessel

The shielding of radioactivity from outside the nitrogen is shown in figure 8. It shows the distribution of the points of nearest interaction of each simulated event measured as a distance from the center of the detector. The number of simulated ^{208}Tl decays is $6\cdot 10^8$. The starting points are randomly distributed inside the 2 cm thick steel vessel surrounding the nitrogen. The radioactivity drops 0.8 orders of magnitude per meter diameter. Liquid argon, which is shown as well, has a doubled attenuation coefficient, because of the doubled density.

From simulation of 1.1 billion ^{208}Tl decays in the steel vessel only 8 deposit

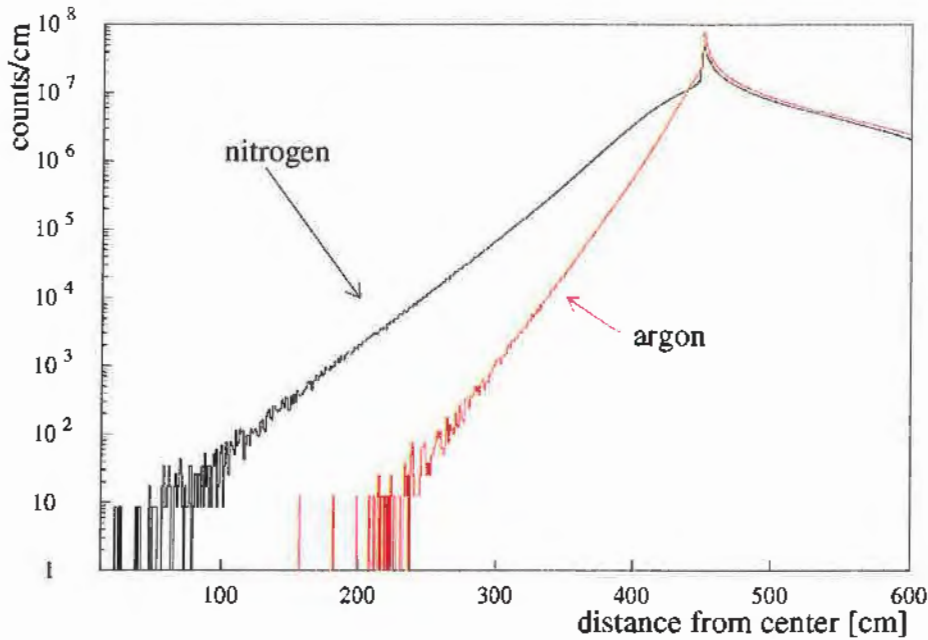


Figure 8: Simulation of ^{208}Tl activity randomly distributed in the wall of the vessel; the histogram contains for each event the distance of the nearest interaction to the detector center; for comparison filling of liquid nitrogen (black) and argon (red) are simulated.

energy in a Germanium detector (see figure 9 and 8), due to the shielding of the liquid nitrogen. This means, an impurity concentration of $1 \cdot 10^{-8}$ g/g U/Th (40 mBq/kg) in the steel vessel would contribute to the count rate in the Ge detectors as much as the impurities in the nitrogen.

The shielding of radioactivity from outside the tank is not simulated yet. But a first estimation can be made from the simulation of impurities inside the steel vessel. Assuming that the 2 cm thick steel (7.9 g/cm^3) vessel has no shielding effect the activity of 40 mBq/kg can be converted into a flux of $3.2 \cdot 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$, which is by a factor of 50 lower than the flux of ^{208}Tl 2.6 MeV photons of $1.5 \cdot 10^{-2} \text{ cm}^{-2} \text{ s}^{-1}$ measured in hall C of the Gran Sasso lab. Therefore an additional shielding of for example 10 cm lead or 0.8 m liquid nitrogen has to be applied.

2.4.5 Muon induced background

To study the influence of muons penetrating the Gran Sasso rock we simulated a flux of $2.3 \cdot 10^{-4} \text{ muons/m}^2 \cdot \text{s}$ with 200 GeV [62] crossing the tank from the top. The induced events in the germanium detectors are shown in figure 9. The dashed histogram contains all events, whereas the filled histogram contains only single hit

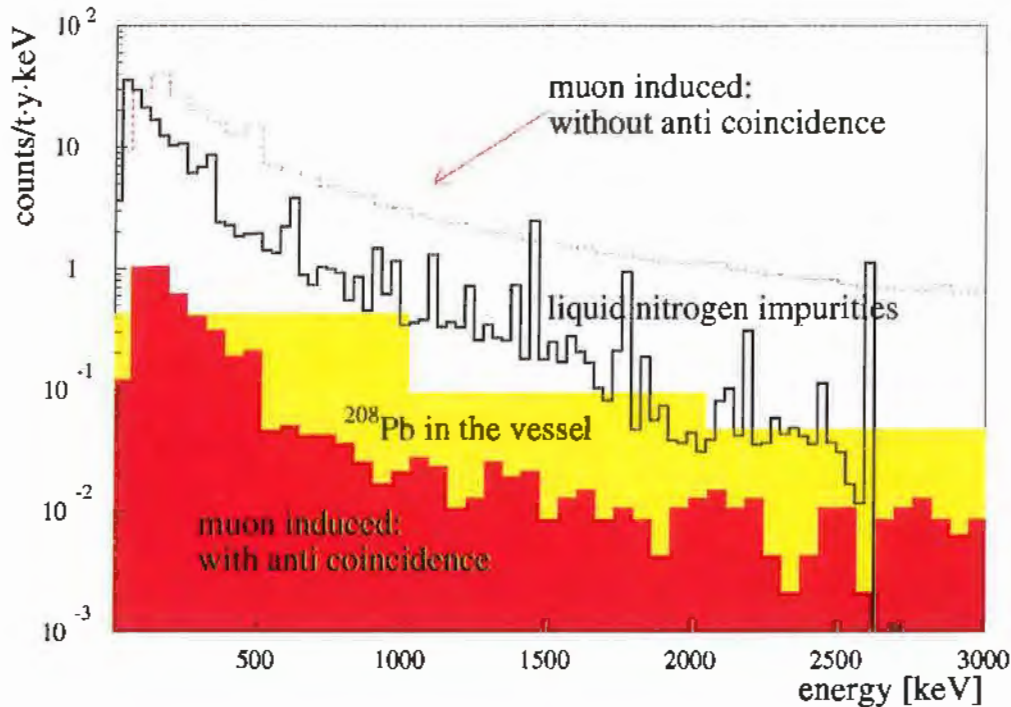


Figure 9: Background from outside the nitrogen: 200 GeV muons induced events (red line) and single hit events (red filled histogram); decay of ^{208}Tl in the steel vessel (yellow histogram) and the background originating from the nitrogen impurities for comparison (thick line).

events. A count rate reduction by two orders of magnitude through coincidence of germanium detectors from muon induced showers can be seen. Thus, application of this technique is sufficient to reduce the muon induced background far below background from natural radioactivities.

The structure, which holds the detectors, should have, according to the simulation of a single detector, the same purity level as the nitrogen. The possibility to obtain organic substances with 10^{-16}g/g purity levels was demonstrated by the liquid scintillator operated in CTF.

2.5 Expected Results

If no positive signal for $0\nu\beta\beta$ decay will be observed, limits on the neutrino mass can be calculated. Assuming a radioactive background as stated above the GENIUS experiment should measure after one year 0.8 events in the peak region of the neutrinoless double beta decay. From this number results, following the procedure for analysis recommended by [63], which is highly conservative and not used in the analysis of several other $\beta\beta$ experiments, a 68 % upper limit on

the number of $0\nu\beta\beta$ decays of 1.2. It corresponds to a lower half life limit to be obtained in one year of measurement of:

$$T_{1/2}^{0\nu} \geq 5.8 \cdot 10^{27} y \quad (\text{with } 68\% \text{ C.L.}) \quad (7)$$

Using the matrix elements of [64] the half life limit can be converted into an upper limit on the neutrino mass of:

$$\langle m_\nu \rangle \leq 0.02 eV \quad (\text{with } 68\% \text{ C.L.}) \quad (8)$$

Figure 10 shows the obtainable limits on the neutrino mass in the case of zero background. This assumption might be justified since our assumed impurity concentrations are still more conservative than proved already now for example by Borexino. The final sensitivity of a one ton experiment can be defined by the limit, which would be obtained after 10 years of measurement. For the one ton experiment this would be:

$$T_{1/2}^{0\nu} \geq 6.4 \cdot 10^{28} y \quad (\text{with } 68\% \text{ C.L.}) \quad (9)$$

and

$$\langle m_\nu \rangle \leq 0.006 eV \quad (\text{with } 68\% \text{ C.L.}) \quad (10)$$

The ultimate experiment could test the $0\nu\beta\beta$ half life of ${}^{76}\text{Ge}$ up to a limit of $5.7 \cdot 10^{29} y$ and the neutrino mass down to $2 \cdot 10^{-3} eV$ using 10 tons of enriched Germanium.

The expected background according to the simulation of 10 counts/keV·y·t in the energy range below 100 keV leads to a sensitivity of GENIUS for the dark matter as shown in Fig. 20. Even use of a smaller amount of detector material would be possible. The measuring time increases from 100 days up to, still reasonable, 3 years from a one ton to a 100 kg version of GENIUS. However, an experiment using one ton of Germanium could search for the seasonal WIMP signal in one or two years [86]. If no signal would be observed, the limits would improve with the measuring time. The WIMP search does not require the use of enriched Germanium because the obtainable limits depend on the achieved background level. Furthermore, a spin-dependent WIMP–nucleon coupling could be tested using enriched ${}^{73}\text{Ge}$ (see [8, 86]).

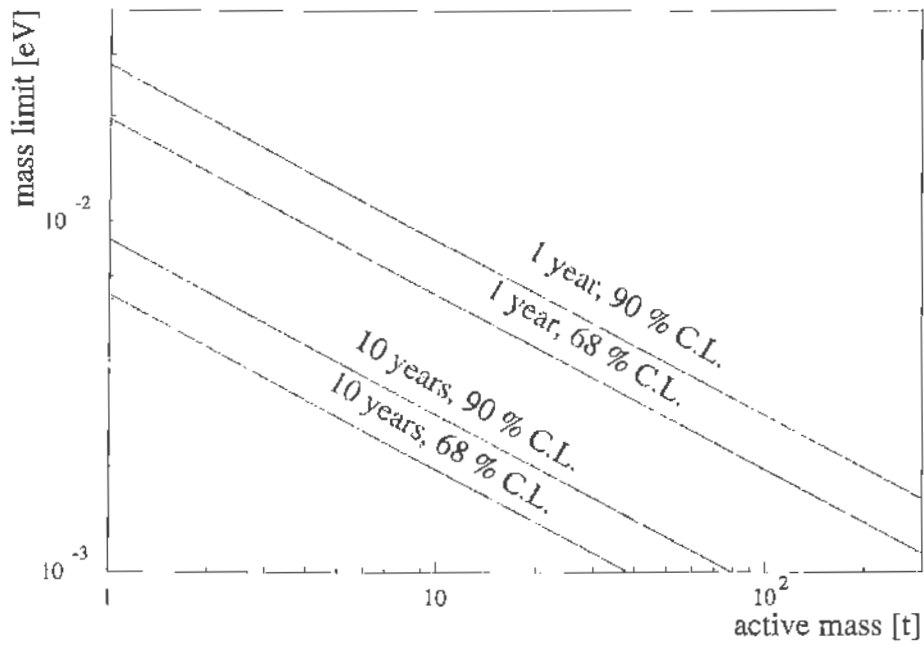


Figure 10: Mass limits on Majorana neutrino mass after one and ten years measuring time as function of the active detector mass; zero background is assumed.

3 Physics of GENIUS

3.1 Neutrino Masses and Double Beta Decay

For unmixed neutrinos the limit obtainable by GENIUS would render the electron neutrino definitely uninteresting for cosmology, ruling out ν_e as a sensible hot dark matter candidate. However, $\langle m_\nu \rangle$ is in general not equal to the electron neutrino mass. Once neutrinos have finite masses it is natural to assume that mass eigenstates are no longer weak interaction eigenstates, and mixing among different neutrino generations occurs, analogously to the observed mixing in the quark sector. Allowing for finite mixing among different generations for $\langle m_\nu \rangle$ one has to define:

$$\langle m_\nu \rangle = \sum_j' U_{ej}^2 m_j, \quad (11)$$

where the prime indicates that the sum extends over light neutrino mass eigenstates ($m_j \leq 10$ MeV) only.

Taking into account finite mixing, although complicating the analysis considerably, leads to interesting information once the sub-eV range is explored by double beta decay experiments. The consequences of eq. (11) for GENIUS are discussed in detail in the next sections.

3.1.1 General Definitions for the Neutrino Mixing Matrix

One can define a general mixing matrix for neutrinos, which in the Dirac case can be written exactly in the form of the CKM matrix:³

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \quad (12)$$

where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$ and δ is a CP-violating phase. This matrix can be decomposed into a product of three unitary matrices:

$$U = U_{23} \cdot U_{13} \cdot U_{12}, \quad (13)$$

where

$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \quad (14)$$

³This section assumes three neutrino flavors. Including a fourth, sterile neutrino is straightforward.

$$U_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}, \quad (15)$$

$$U_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (16)$$

In the Majorana case, however, the matrix eq. (12) has to be generalized, since for Majorana neutrinos one can have $n = N(N - 1)/2$ CP-violating phases [65]. For Majorana neutrinos, therefore U is given by:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{-i\delta_{12}} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}e^{i\delta_{12}} - c_{12}s_{23}s_{13}e^{i(\delta_{13}+\delta_{23})} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i(\delta_{23}+\delta_{13}-\delta_{12})} & s_{23}c_{13}e^{i\delta_{23}} \\ s_{12}s_{23}e^{i(\delta_{23}+\delta_{13})} - c_{12}c_{23}s_{13}e^{i(\delta_{23}+\delta_{13})} & -c_{12}s_{23}e^{i\delta_{23}} - s_{12}c_{23}s_{13}e^{i(\delta_{13}-\delta_{12})} & c_{23}c_{13} \end{pmatrix} \quad (17)$$

Eq. (17) is the most general Majorana neutrino mixing matrix for three generations.

Note, however, that the CP-violating phases can be defined only up to arbitrary factors of i , i.e. up to rotations by factors of $\pi/2$.⁴ Because of this freedom, one can find different conventions for eq. (17) in the literature. The conventions used in [66] correspond to the replacements $\delta_{12} \rightarrow -2\beta$ and $\delta_{13} \rightarrow -(\beta + 3\gamma - 2\delta)$ in eq. (17). In the following the conventions of [66] are used. The effective neutrino mass, measured in $0\nu\beta\beta$ decay, is then given by,

$$\langle m_\nu \rangle = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\beta} + s_{13}^2 m_3 e^{i(\beta + 3\gamma - 2\delta)}|. \quad (18)$$

Thus, in general $\langle m_\nu \rangle$ is a function of a priori seven unknown quantities.

3.1.2 Considering two Generations only

It is instructive to analyze the simpler case of two generations first, before doing a full analysis of eq. (18).⁵ In the formalism given in the previous section this simply corresponds to setting either s_{13} or s_{12} equal to zero. It should be noted, that both cases are logically equivalent, as far as our analysis of double beta decay is concerned. Only the case $s_{13} = 0$ is therefore discussed. The case $s_{12} = 0$ can be obtained from the formulas given in this section by obvious replacements.

The effective neutrino mass in this scenario is then

$$\langle m_\nu \rangle = |c_{12}^2 m_1 + s_{12}^2 m_2 e^{2i\beta}|. \quad (19)$$

⁴Observables, such as $\langle m_\nu \rangle$ can depend on relative signs, but never on the absolute sign of the mixing matrix.

⁵Considering only two generations is an assumption used in most studies of neutrino oscillations, although it is valid only for appearance experiments, but should not be used in disappearance experiments, as for example the current solar neutrino experiments.

Let us first discuss the CP-conserving case. In this case $c^{2i\theta}$ reduces to $\eta = +1, -1$. Furthermore, for the masses one can discuss two extreme cases: A) $m_1 \ll m_2$ and B) $m_1 \approx m_2$. The case A) is usually denoted as “hierarchical” (a typical realization being for example the simplest version of the seesaw mechanism [67]), while B) is usually called “degenerate” scenario. (Degenerate scenarios have been widely discussed in the literature recently, see for example [14], or the review in [47].)⁶

The most simple case is found assuming $c_{12}^2 m_1 \ll \eta s_{12}^2 m_2$, since then the value of η is insignificant.

$\langle m_\nu \rangle$ can be written as

$$\langle m_\nu \rangle = \frac{1}{2} m_2 (1 - \sqrt{1 - \sin^2 2\theta}), \quad (20)$$

which allows one to express the double beta decay observable in terms of the usual neutrino oscillation parameters,

$$\Delta m_{21}^2 \approx m_2^2 = \frac{4\langle m_\nu \rangle^2}{(1 - \sqrt{1 - \sin^2 2\theta})^2}. \quad (21)$$

Being a bit more general, as assumed in case A), one should keep the corrections of the order (m_1/m_2) , such that

$$\langle m_\nu \rangle = m_2 \left| \left(\frac{m_1}{m_2} \right) + \frac{1}{2} (1 - \sqrt{1 - \sin^2 2\theta}) \left(\pm 1 - \left(\frac{m_1}{m_2} \right) \right) \right|. \quad (22)$$

Also,

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = m_2^2 \left(1 - \left(\frac{m_1}{m_2} \right)^2 \right). \quad (23)$$

Rewriting eq. (22)

$$m_2 = \frac{\langle m_\nu \rangle}{\left| \left(\frac{m_1}{m_2} \right) + \frac{1}{2} (1 - \sqrt{1 - \sin^2 2\theta}) \left(\pm 1 - \left(\frac{m_1}{m_2} \right) \right) \right|}, \quad (24)$$

one sees that one can express the $0\nu\beta\beta$ decay observable in terms of oscillation parameters, once some assumption about the ratio m_1/m_2 is made. Typical assumptions would be either the quadratic seesaw ($m_1 : m_2 = m_e^2 : m_\mu^2$) or the linear seesaw relations ($m_1 : m_2 = m_e : m_\mu$). Degenerate models, see below, correspond to $m_1/m_2 \approx 1$ (see footnote 7). Note, that in case of a positive value for η eq. (24) gives always more stringent limits than using eq. (21), while for

⁶Again, one could have a third case $m_2 \ll m_1$, which is logically equivalent.

negative η the results are very similar to those for positive η except for the small region in the parameter space, where

$$m_1 = m_2 \tan^2 \theta. \quad (25)$$

The sensitivity of $0\nu\beta\beta$ decay on neutrino oscillation parameters using eq. (21) and eq. (24) for various $R \equiv (m_1/m_2)$ for an assumed limit on the effective mass of $\langle m_\nu \rangle \leq 0.01$ eV is shown in fig. 11. The figure nicely illustrates that the limit where $R \rightarrow 0$, corresponding to the ‘‘complete hierarchy’’ models, is something of a worst-case scenario for $0\nu\beta\beta$ decay in terms of sensitivity on oscillation parameters, while for the degenerate neutrino mass scenarios, favored in many recent papers [14], $0\nu\beta\beta$ decay is especially sensitive. Non-observation of $0\nu\beta\beta$ decay at the level of sensitivity of GENIUS with 1 ton would either require a negative CP-phase between the two neutrinos and maximal mixing at the same time or definitely rule out degenerate neutrino mass scenarios with neutrinos as hot dark matter candidates.

Let us now consider case B) $m_1 \approx m_2$. $\langle m_\nu \rangle$ in this case is simply:

$$\langle m_\nu \rangle = m |\cos^2 \theta \pm \sin^2 \theta|, \quad (26)$$

which depending on the CP-sign gives

$$\langle m_\nu \rangle = m \quad \text{if } \eta = +1, \quad (27)$$

$$\langle m_\nu \rangle = m |\sqrt{1 - \sin^2 2\theta}| \quad \text{if } \eta = -1. \quad (28)$$

Thus, in the degenerate, two-generation scenario with positive CP-sign, double beta decay measures directly the average neutrino mass, while for a negative CP-sign we can express $\langle m_\nu \rangle$ again in terms of oscillation parameters.

Let us finally briefly discuss the case of an arbitrary CP-violating phase β . The consequences of an arbitrary β is most easily seen for case B), the degenerate scenario. $\langle m_\nu \rangle$ is then given by

$$\langle m_\nu \rangle = m |\sqrt{1 - \sin^2 \beta \sin^2 2\theta}|. \quad (29)$$

Obviously the lesson to be learned from eq. (29) is twofold. If $0\nu\beta\beta$ decay is not discovered one can always stick to the CP-conserving case, since arbitrary values of β lead always to limits which are more stringent than for the CP-conserving case of $\sin \beta = 1$. And, second, if effects of finite neutrino masses are discovered in both, neutrino oscillation experiments and double beta decay, the $0\nu\beta\beta$ decay data can give a measurement of CP-violation in the neutrino sector. One should keep in mind, however, that this discussion is based on the 2-generation scenario.

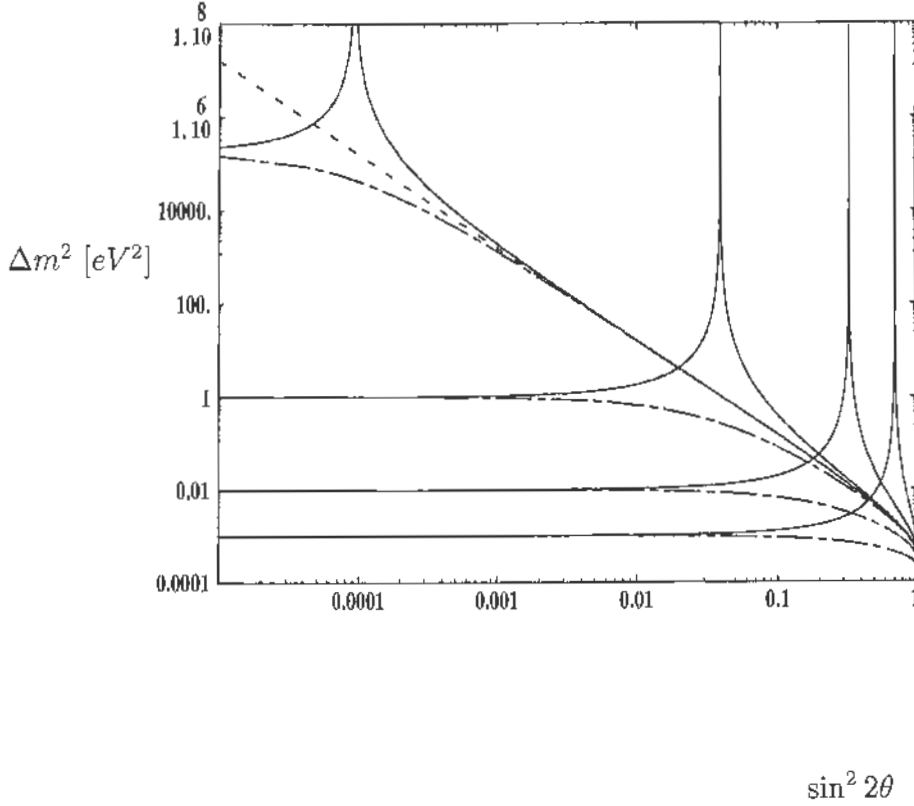


Figure 11: Oscillation parameters and neutrinoless double beta decay in two generation scenarios, under the assumption of a limit on the effective neutrino mass of $\langle m_\nu \rangle \leq 0.01$ eV. The dashed curve corresponds to the “complete hierarchy” case, when only the heavier mass eigenstate contributes to $0\nu\beta\beta$ decay. Dot-dashed and full curves are for $\eta^{CP} = \pm 1$, respectively, for various assumed values of $R = (m_1/m_2)$. From top to bottom (left to right) for $\eta^{CP} = +1$ ($\eta^{CP} = -1$): $R = (m_e/m_\mu)^2$, 0.01, 0.1 and 0.3. The first case corresponds to the classical quadratic seesaw, large ratios, say $R \geq 0.3$, to the recently often discussed “degenerate” models. Regions above the lines would be excluded if $0\nu\beta\beta$ decay is not found.

3.1.3 More Complex: Three Generations

The effective neutrino mass in full generality is given by eq. (18). Again it is easier to consider the CP-conserving case, when the CP-phases can take only discrete values of $(\eta_1, \eta_2, \eta_3) = (+, +, +); (+, +, -); (+, -, +)$ and $(+, -, -)$. For an, albeit not complete analysis including CP-violation, see ref. [66].

Having three, a priori unknown and different masses contributing to $\langle m_\nu \rangle$

Table 3: The 13 different logical possibilities for ratios of neutrino masses. Note, that all four variants have been discussed in the literature.

Scenario	Comment	Relation
A)	Hierarchy	$m_i \ll m_j \ll m_k$
B)	Partial degeneracy	$m_i \ll m_j \approx m_k$
C)	Inverted partial degeneracy	$m_i \approx m_j \ll m_k$
D)	Complete degeneracy	$m_i \approx m_j \approx m_k$

there are a number of different logical possibilities. They are summarized in table 3.

The first case of table 3 corresponds to the classical seesaw expectation, if $i = 1$, $j = 2$ and $k = 3$ [67]. However, recently also other cases have been discussed in great detail in the literature. Especially, the complete degenerate models have attracted some attention, because particle physics models for such a scenario can be realized relatively easily [14].⁷

Since practically all models of neutrino masses have been invented to explain currently known hints from experiments, most studies concentrated on the case where neutrino masses are ordered in the same way as those of the charged leptons, i.e. $i < j < k$. However, this need not be the case in general. For example, the electron neutrino could be heavier than the muon neutrino etc. Nevertheless this discussion will take the same attitude and only briefly comment on the other cases with inverted mass hierarchy near the end of this section.

Having specified all possibilities, it is seen that the complete degenerate scenario, scenario D), is relatively simple to analyze. For $\langle m_\nu \rangle$ one has

$$\langle m_\nu \rangle = m |c_{12}^2 c_{13}^2 \pm s_{12}^2 c_{13}^2 \pm s_{13}^2|. \quad (30)$$

Depending on the relative CP-signs double beta decay is sensitive to

$$\langle m_\nu \rangle = m \quad \text{for } (+, +, +) \quad (31)$$

$$\langle m_\nu \rangle = m |1 - 2s_{13}^2| \quad \text{for } (+, +, -) \quad (32)$$

$$\langle m_\nu \rangle = m |1 - 2s_{12}^2 c_{13}^2| \quad \text{for } (+, -, +) \quad (33)$$

$$\langle m_\nu \rangle = m |1 - 2c_{12}^2 c_{13}^2| \quad \text{for } (+, -, -) \quad (34)$$

⁷One could call mass models where mass ratios are not exactly, but approximately equal to one “quasi-degenerate”. We will use this terminology in the following, whenever ratios of masses are in the range of $0.01 \leq R_{ij} \leq 100$.

Non-observation of $0\nu\beta\beta$ decay defines allowed bands of mixing angle combinations in the plane (s_{12}, s_{13}) . In the case where all CP-signs are positive, $\langle m_\nu \rangle$ coincides with m ⁸.

Fig. 12 shows current and future constraints on completely degenerate 3-generation scenarios for assumed values of the average neutrino mass m for different choices of the relative CP phases. The horizontal bands correspond to the case of $(+, +, -)$, the bands extending to $\sin^2 \theta_{13} = 0$ to $(+, -, +)$ and the bands extending to $\sin^2 \theta_{13} = 1$ to $(+, -, -)$. Note that an analysis similar to the one in fig. 12. has been done recently in [66].

However, for a more complete analysis, one should not fix the average neutrino mass at some preferred value. Instead, constraints on neutrino mixing parameters should be calculated as a function of the average neutrino mass. This is shown in fig. 13., for an assumed limit on $\langle m_\nu \rangle$ of $\langle m_\nu \rangle \leq 0.01$ eV. The figure clearly illustrates that only if large cancelations between the different contributions from the different mass eigenstate occur, $0\nu\beta\beta$ decay will not occur for neutrinos in the interesting mass range of hot dark matter. On the other hand, if all CP-phases would be positive, $0\nu\beta\beta$ decay will either be observed or no neutrino mass can be larger than 0.01 eV.

Next, it is easy to realize that case A) can be also very simple: If the hierarchy is very strong, say as in the quadratic seesaw models, it is sufficient to go back to eq. (21).

In case the degeneracy is not complete or if there is only partial degeneracy, one should keep corrections, scaling out the presumably largest mass,

$$\begin{aligned} \langle m_\nu \rangle &= m_3 |c_{12}^2 c_{13}^2 \left(\frac{m_1}{m_3}\right) \pm s_{12}^2 c_{13}^2 \left(\frac{m_2}{m_3}\right) \pm s_{13}^2| \\ &= m_3 |c_{12}^2 c_{13}^2 R_{13} \pm s_{12}^2 c_{13}^2 R_{23} \pm s_{13}^2|. \end{aligned} \quad (35)$$

For the various partially degenerate models $\langle m_\nu \rangle$ can then be easily obtained by setting the corresponding R_{ij} 's equal to one and zero. For example, if m_1 is the mass eigenstate which is dominantly an electron neutrino in flavor space and it is assumed that $m_1 \ll m_2 \simeq m_3 =: m$, one finds,

$$\langle m_\nu \rangle = m |s_{12}^2 c_{13}^2 \pm s_{13}^2|.$$

All other logically possible cases can be derived analogously.

Let us finally briefly comment on inverted hierarchy models. It is clear that if neutrino masses would not follow the same pattern as the masses of the charged leptons, i.e. the electron neutrino being heavier than the muon and tau neutrinos,

⁸This case is already on the edge of being excluded, as far as neutrinos as hot dark matter candidates are concerned.

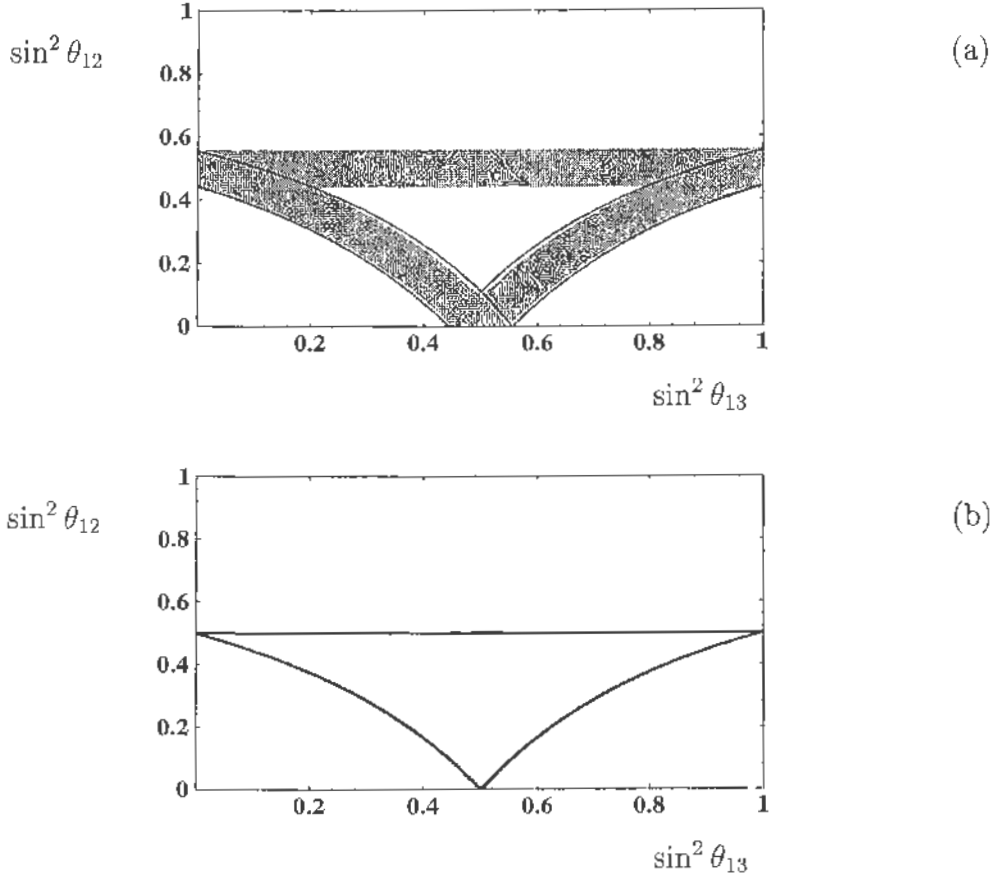


Figure 12: Allowed bands in the plane ($\sin^2 \theta_{12} - \sin^2 \theta_{13}$) for a completely degenerate 3-generation scenario for different combinations of the CP-eigenvalues, see text. a) current limit $\langle m_\nu \rangle \leq 0.5$ eV and assumed average mass of $m = 4.5$ eV. b) GENIUS sensitivity for $\langle m_\nu \rangle = 0.01$ eV and average mass of $m = 2$ eV. Note, that in the case of GENIUS the allowed ranges are even smaller than the thickness of the lines shown.

$0\nu\beta\beta$ decay would be especially well suited to search for neutrino masses. Under such a - rather strange - assumption non-observation of $0\nu\beta\beta$ in GENIUS simply would rule out any neutrino masses above $\langle m_\nu \rangle$, i.e. inverted neutrino mass models could not provide dark matter candidates.

To summarize the discussion on the three-generation scenarios, it can be stated that only a limited number of possible cases for neutrino mass ratios can exist. Limits on all cases can be derived by an appropriate reformulation of the definition of $\langle m_\nu \rangle$. $0\nu\beta\beta$ decay is especially sensitive to degenerate or quasi-degenerate models. For strongly hierarchical neutrino mass models it is possible to do the analysis by simply going back to the simpler two generation scenarios.

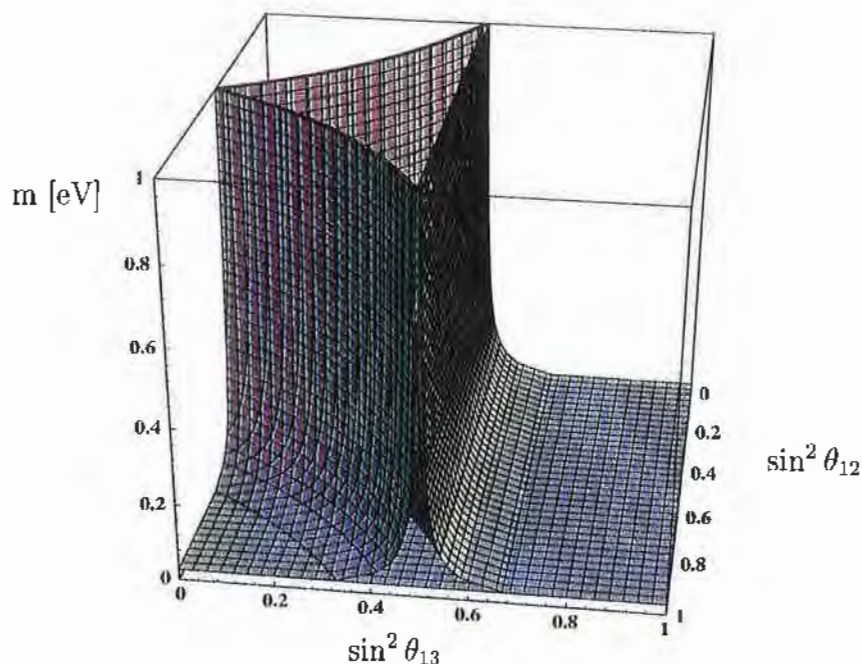


Figure 13: 3-dimensional exclusion plot for the 3-generation degenerate neutrino scenario. Note that the range of m is from 0 to 1 eV. Excluded are all combinations of neutrino parameters which do not lie in between the three small areas enclosed by the six different shaded planes. The three ($\times 2$) different planes correspond to the three cases for different combinations of CP-phases, compare to figure 12. Cuts at constant values of m lead to figures such as those of fig. 12.

3.2 Sensitivity for Neutrino Mass and Oscillation Compared to other Experiments

As should be clear from the discussion given above, a comparison between double beta decay and neutrino oscillation experiments always requires that some assumptions about neutrino mass ratios are made. In addition, as has also been mentioned above, in general one should analyze the complete three generation problem in order to get reliable results. However, most oscillation experiments have been analyzed for two generations only, although such an approach is only appropriate for appearance experiments. Nevertheless, for the ease of comparison most of the discussion will stick to the two generation case.

Let's first discuss the case $\sin^2 \theta_{12} = 0$. In this case double beta decay can be compared in sensitivity to experiments searching for $\nu_e - \nu_\tau$ oscillations. Fig. 14 gives a summary of currently existing limits and future experimental sensitivity

in the $\Delta m_{13}^2 - \sin^2(2\theta_{e\tau})$ plane. The (background) figure is taken from ref. [68].

The shaded area in fig. 14 is the currently excluded region by the BUGEY reactor experiment [69]. The thin line is the sensitivity of the currently running CHORUS/NOMAD experiments at CERN. Dotted and dash-dotted lines are for future accelerator experiments, for details see [68]. In addition, the region where neutrinos are relevant for the dark matter is indicated. One can see that information on tau neutrinos at present is rather scarce, mainly limited to large mixing angles.

The two thick (solid and dashed) lines are sensitivities for future double beta decay experiments if one assumes a strong hierarchy between m_{ν_e} and m_{ν_τ} . The dashed line is for GENIUS with one ton while the full line assumes a limit on $\langle m_\nu \rangle$ of $\langle m_\nu \rangle = 0.001$ eV (GENIUS with 10 tons). While already GENIUS is competitive to NAUSICAA-CERN it would be necessary to go down to 10^{-3} eV, i.e. GENIUS with 10 tons, to really cover a significant new part of the parameter space - if neutrino masses are strongly hierarchical. For degenerate or quasi-degenerate neutrino mass models already GENIUS with 1 ton would be more sensitive than all currently planned accelerator neutrino oscillation experiments.

One can draw similar curves for $0\nu\beta\beta$ decay experiments assuming $\sin^2\theta_{13} = 0$, for $\nu_e - \nu_\mu$ oscillations, see fig. 15. The (background) figure is taken from [70]. It shows a number of reactor and accelerator data, together with the GENIUS $0\nu\beta\beta$ decay experimental sensitivities for strong $m_{\nu_e} - m_{\nu_\mu}$ hierarchy for $\langle m_\nu \rangle = 0.01$ (dashed) and $\langle m_\nu \rangle = 0.001$ (full) lines. While the GENIUS 1 ton sensitivity is sufficient (even for this worst case $m_{\nu_e} \ll m_{\nu_\mu}$) to extend the reach on Δm^2 down to smaller values at large mixing angles, for a large part of the parameter space there exists already a number of constraints. In addition, upcoming oscillation experiments will also be sensitive to smaller Δm^2 . A $0\nu\beta\beta$ decay experiment with $\langle m_\nu \rangle \leq 0.001$ (GENIUS, 10 tons), on the other hand, would have a sensitivity better than all existing or planned oscillation experiments, at least at large $\sin^2 2\theta$, already in the worst case scenario of $R = 0$. As in the case of $\nu_e - \nu_\tau$ oscillations assuming a larger value of R increases the sensitivity of GENIUS on oscillation parameters.

Fig. 16 shows the region in parameter space relevant for the atmospheric neutrino problem for $\nu_e \leftrightarrow \nu_\mu$ oscillations. The original figure is again taken from ref. [70]. The dashed line is for $\langle m_\nu \rangle \leq 0.01$ (GENIUS 1t) the full line for $\langle m_\nu \rangle \leq 0.001$ eV (GENIUS 10t), again for the (worst) strong hierarchical neutrino mass scenario. GENIUS with 1 ton would already be able to test the $\nu_e \leftrightarrow \nu_\mu$ hypothesis.

Figure 17 compares GENIUS double beta decay to the LSND results. The original figure (upper left) is taken from [44]. The case where neutrino masses are strongly hierarchical, including $0\nu\beta\beta$ decay constraints for $\langle m_\nu \rangle = 0.01$ (full) and $\langle m_\nu \rangle \leq 0.001$ (dashed) line, is shown to the upper right. It would need an experiment sensitive to $\langle m_\nu \rangle = 10^{-3}$ eV (GENIUS 10 tons) in this scenario to probe most parts of the relevant parameter space.

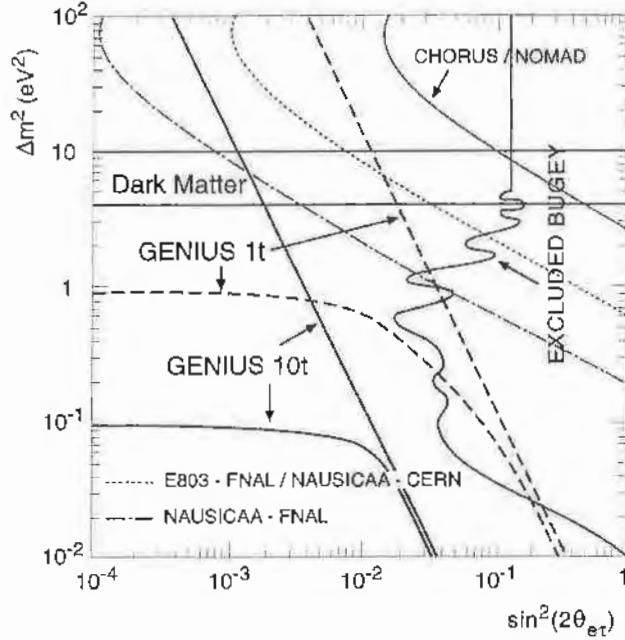


Fig. 14: Current limits and future experimental sensitivity on $\nu_e - \nu_\tau$ oscillations. The shaded area is currently excluded from reactor experiments. The thin line is the estimated sensitivity of the CHORUS/NOMAD experiments. The dotted and dash-dotted thin lines are sensitivity limits of proposed accelerator experiments, NAUSICAA and E803-FNAL [68]. The thick lines show the sensitivity of GENIUS (broken line: 1 t, full line: 10 t), for two examples of mass ratios. The straight lines assume that the lighter mass eigenstate has zero mass ($R=0$), while the lines bend to the left assume $R = 0.01$.

The lower two figures show the LSND region plus GENIUS, but now also for cases where the lower neutrino mass eigenstate is not exactly equal to zero. To the left is shown the case where $\eta^{CP} = +1$ for three values of the ratio $R = m_1/m_2$. The lower (upper) curve is for an assumed R of $R = 0.02$ ($R = 0.01$), while the straight line is for $R = 0$. Even for m_{ν_e} as low as $2 \times 10^{-2} m_{\nu_\mu}$ GENIUS with 1 ton would be sufficient to find $0\nu\beta\beta$ decay, if the LSND result is to be explained in terms of neutrino oscillations. The figure to the right shows the influence of η^{CP} . The three curves for GENIUS are for $R = 0$ (middle curve), the other two lines are for $R = 0.01$ and $\eta^{CP} = \pm 1$, respectively. Negative η^{CP} allows certain ranges of oscillation parameters to be consistent with non-observation of $0\nu\beta\beta$ decay.

Finally, fig. 18 shows a summary of currently available information on neutrino oscillation parameters, including possible $0\nu\beta\beta$ decay sensitivities for $\eta^{CP} = +1$: The full lines are for GENIUS 1 ton, while the dashed lines assume $\langle m_\nu \rangle \leq 10^{-3}$ eV (GENIUS 10 tons). The lines are for $R = 0, 0.01, 0.1$, respectively.

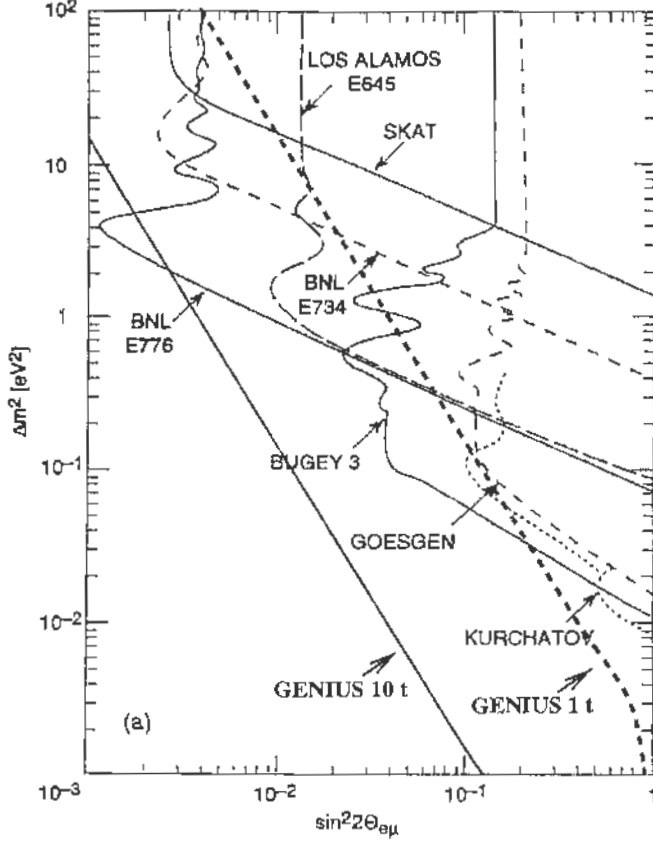


Figure 15: Current limits on $\nu_e - \nu_\mu$ oscillations. Various existing experimental limits from reactor and accelerator experiments are indicated, as summarized in ref. [70]. In addition, the figure shows the expected sensitivities for GENIUS with 1 ton (thick broken line) and GENIUS with 10 tons (thick, full line.)

According to this result already GENIUS 1 ton tests all degenerate or quasi-degenerate neutrino mass models in any range where neutrinos are interesting for cosmology and also would test the atmospheric neutrino problem if it is due to $\nu_e \leftrightarrow \nu_\mu$ oscillations. GENIUS in its 10 ton version would directly test the large angle solution of the solar neutrino problem.

3.3 GENIUS and other Physics Beyond the SM

3.3.1 Left-Right Symmetry

$0\nu\beta\beta$ decay can be sensitive to the possible existence of right-handed W -bosons if heavy right-handed neutrinos exist [21, 22]. The current limit on m_{W_R} from absence of $0\nu\beta\beta$ decay is about 1.1 TeV (for a heavy right-handed neutrino mass

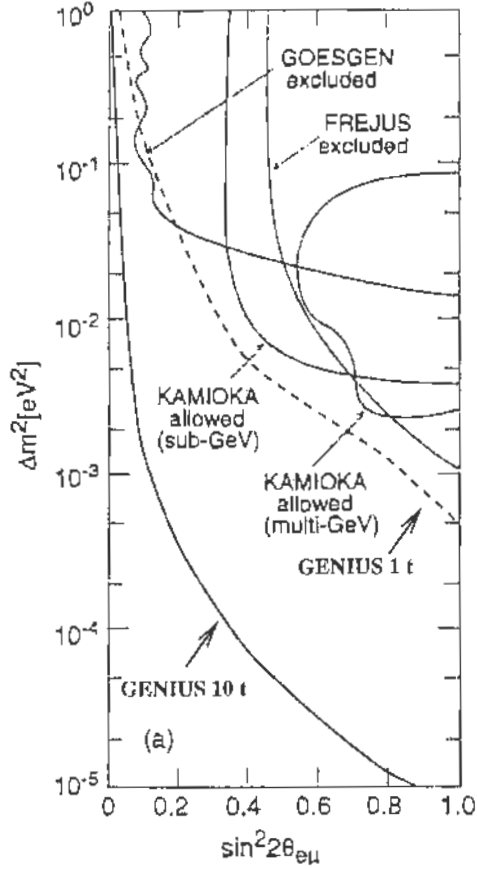


Figure 16: Oscillation parameters which solve the atmospheric neutrino problem for $\nu_e \leftrightarrow \nu_\mu$ oscillations. In addition the best currently existing reactor constraints are shown. GENIUS would be able to test the atmospheric neutrino problem already with 1 ton.

of 1 TeV) [22], better than any existing direct constraint and comparable to the theoretical limit derived from the $K^0 - \bar{K}^0$ mass difference. Note that the latter has large theoretical uncertainties, which makes improvements of this limit rather difficult.

If GENIUS is able to reach down to $\langle m_\nu \rangle \leq 0.01$ eV, it would at the same time be sensitive to right-handed W -boson masses up to $m_{W_R} \geq 8$ TeV (for a heavy right-handed neutrino mass of 1 TeV) or $m_{W_R} \geq 5.3$ TeV (at $\langle m_N \rangle = m_{W_R}$). Such a limit would be comparable to the one expected for the LHC, see for example [71], which quotes a final sensitivity of something like 5 – 6 TeV. Note, however that in order to obtain such a limit the experiments at the LHC need to accumulate about $100 fb^{-1}$ of statistics. A 10 ton version of GENIUS could even reach a sensitivity of $m_{W_R} \geq 18$ TeV (for a heavy right-handed neutrino mass of

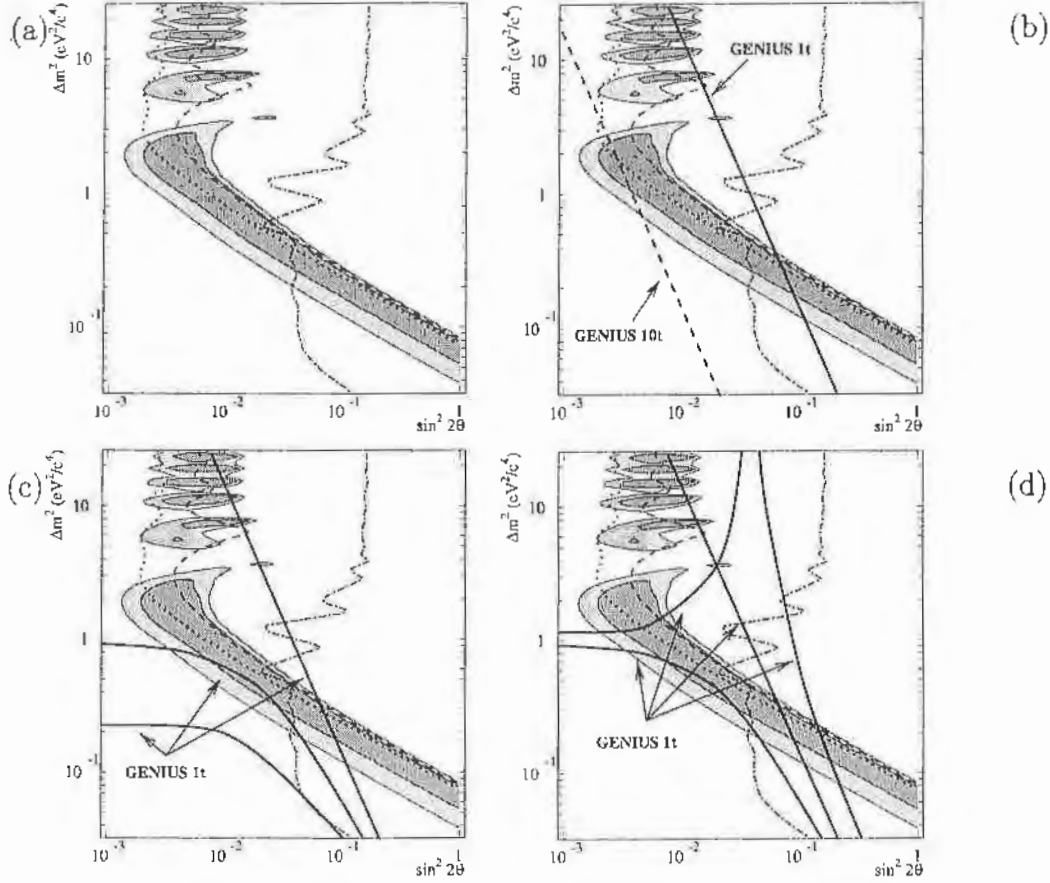


Figure 17: LSND and GENIUS for various scenarios. To the upper left, a) The original LSND result. To the upper right, b) LSND compared to the sensitivity of GENIUS 1 ton (full line) and GENIUS 10 ton (broken line), assuming the worst-case scenario of completely hierarchical neutrino masses. To the lower left, c): LSND compared to the sensitivity of GENIUS 1t for $\eta^{CP} = +1$ and three ratios R_{12} , from top to bottom $R_{12} = 0, 0.01, 0.02$. To the lower right, d): GENIUS 1 ton sensitivity for $R_{12} = 0, 0.01$ for $\eta^{CP} = \pm 1$.

1 TeV) or $m_{W_R} \geq 10.1$ TeV (at $\langle m_N \rangle = m_{W_R}$).

As is well-known, left-right symmetric models in general do not fix the scale of left-right symmetry breaking, i.e. there is no upper limit to the W_R mass. Interestingly, however, recently Kuchimanchi and Mohapatra and others [72] have studied supersymmetric versions of the original left-right symmetric model and found that these have some very interesting features. Such SUSY-LR models [72] can at the same time solve the strong CP-problem without the need for an axion and have automatic R-parity conservation, a desirable feature of supersymmetric models, if SUSY is to provide a cold dark matter candidate. The “price” for these

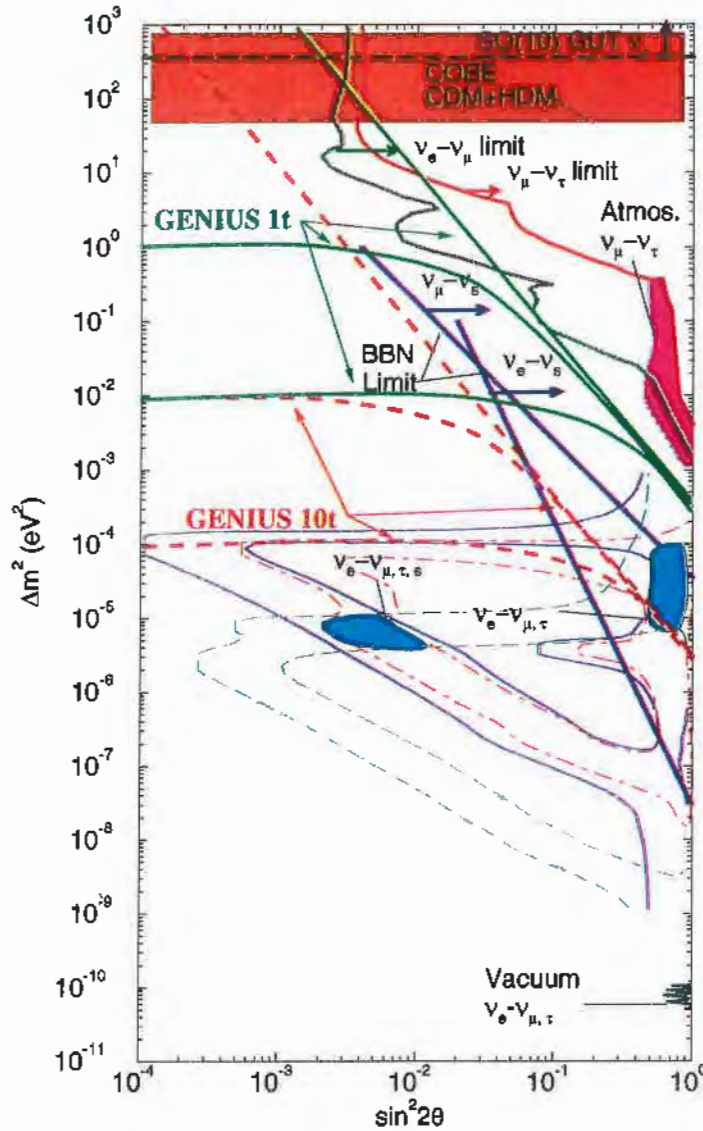


Figure 18: Summary of currently known constraints on neutrino oscillation parameters. The (background) figure without the $0\nu\beta\beta$ decay constraints can be obtained from <http://dept.physics.upenn.edu/www/neutrino/solar.html>. Shown are the vacuum and MSW solutions (for two generations of neutrinos) for the solar neutrino problem, the parameter range which would solve the atmospheric neutrino problem and various reactor and accelerator limits on neutrino oscillations. In addition, the mass range in which neutrinos are good hot dark matter candidates is indicated, as well as limits on neutrino oscillations into sterile states from considerations of big bang nucleosynthesis. Finally the thick lines indicate the sensitivity of GENIUS (full green lines 1 ton, broken red lines 10 ton) to neutrino oscillation parameters for three values of neutrino mass ratios $R = 0, 0.01$ and 0.1 (from top to bottom). While already the 1 ton GENIUS would be sufficient to constrain degenerate and quasi-degenerate neutrino mass models, and also would solve the atmospheric neutrino problem if it is due to $\nu_e \leftrightarrow \nu_\mu$ oscillations, the 10 ton version of GENIUS could cover a significant new part of the parameter space, including the large angle MSW solution to the solar neutrino problem, even in the worst case of $R = 0$.

achievements, however, is that the LR symmetry breaking scale has to be rather low,

$$m_{W_R} \leq \frac{g M_{SUSY}}{f}, \quad (36)$$

where g is the usual $SU(2)$ gauge coupling, f is the Yukawa coupling of the right-handed heavy neutrino and M_{SUSY} is the scale of supersymmetry breaking. Now, if superpartner masses are in the TeV range, as required by the hierarchy arguments, also the right-handed W -bosons should have a mass typically of the order of a few TeV . GENIUS (1 ton) should be able to definitely test such models, if the right-handed neutrinos are not too light (f is not smaller than say 1/10).

3.3.2 R_p SUSY

As is well-known, $0\nu\beta\beta$ decay at present gives already very stringent limits on R-parity violating supersymmetry [24, 25]. Improving the half-life limit for $0\nu\beta\beta$ decay by more than three orders of magnitude, as expected for GENIUS, would then also improve the limits on λ'_{111} by considerable factors.

This is shown in figure 19, where the two full lines to the left are the current TEVATRON limit and the region of sensitivity of HERA. The full line to the right is the expected sensitivity of the LHC (in the limit of large statistics). The three broken lines are (top to bottom) the current constraint and estimated sensitivity of GENIUS 1 ton and GENIUS 10 ton, all for a gluino mass of 1 TeV. If squarks are exceptionally heavy, $m_{\tilde{q}} \geq 1$ TeV, LHC could not compete with GENIUS. However, for typical squark masses below 1 TeV, LHC can finally probe down to smaller couplings than the double beta decay experiment. However, one should keep in mind that LHC can probe squark masses up to 1 TeV only with several years of data taking. Lower statistics shifts the line for LHC to the left.

3.3.3 R-Parity Conserving SUSY

It has recently been realized [26, 27], that R-parity violation is not a necessary ingredient in supersymmetric models for $0\nu\beta\beta$ decay to occur. Instead, extending the MSSM to include Majorana neutrino masses automatically implies that the scalar neutrino has a (B-L)-violating ‘‘Majorana’’ mass, too [27]. Such a ‘‘Majorana’’ sneutrino mass might have interesting consequences for future e^+e^- colliders [27, 73], like for example the NLC.

In such SUSY models with Majorana masses $0\nu\beta\beta$ decay proceeds through the usual mass mechanism, as well as through box diagrams involving loops of supersymmetric particles, for details see [27].

Limits on the (B-L) violating ‘‘Majorana’’ sneutrino mass \tilde{m}_M from the absence of $0\nu\beta\beta$ decay in the Heidelberg-Moscow experiment have been derived [27].

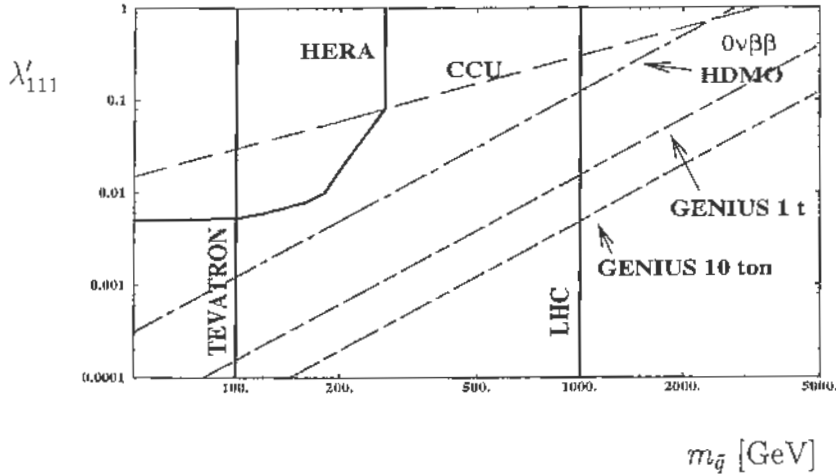


Figure 19: Comparison of sensitivities of existing and future experiments on \tilde{R}_p SUSY models in the plane $\lambda'_{111} - m_{\tilde{q}}$. Note the double logarithmic scale! Shown are the areas currently excluded by the experiments at the TEVATRON, the limit from charged-current universality, denoted by CCU, and the limit from absence of $0\nu\beta\beta$ decay from the Heidelberg-Moscow collaboration ($0\nu\beta\beta$ HDMO). In addition, the estimated sensitivity of HERA and the LHC is compared to the one expected for GENIUS in the 1 ton and the 10 ton version. The figure is essentially an update from ref. [24].

Since limits on \tilde{m}_M scale as $(T_{1/2})^{1/4}$ GENIUS with 1 ton (with 10 tons) would test (B-L) violating “Majorana” sneutrino masses lower by factors of about 7 (20), compared to the present constraints.

3.3.4 Leptoquarks

Leptoquarks have received renewed attention recently, especially due to the unexpected findings at HERA. If leptoquarks exist, in general they should interact with the SM Higgs boson [28]. Such a LQ-Higgs interaction would induce $0\nu\beta\beta$ decay, for LQ-Higgs couplings of the order $\mathcal{O}(1)$ at an unacceptable rate. Absence of $0\nu\beta\beta$ decay thus at present already puts stringent constraints on LQ models.

The scaling of the current limits to the GENIUS (1 ton) sensitivity in such LQ models is simple. Limits on the lepton number violating parameters, defined in [28], improve as $\sqrt{T_{1/2}}$. This means that for LQs in the range of 200 GeV LQ-Higgs couplings down to (few) 10^{-8} could be explored. Putting it the other way round, if leptoquarks interact with the standard model Higgs boson with a coupling of order $\mathcal{O}(1)$ either $0\nu\beta\beta$ decay must be found or LQs must be heavier than (several) 10 TeV(s).

3.3.5 Composite Neutrinos

Although currently there are no hints that quarks and leptons are composite particles, one might speculate that, when exploring higher energy ranges one might hit an energy scale Λ_C at which a new level of substructure becomes visible, see for example [74, 75]. If neutrinos are composite particles, there then should exist excited neutrinos which couple to the ordinary leptons [74, 75].

Panella and Srivastava [76] pointed out, that if the excited neutrinos are of Majorana nature, there should be a contribution to $0\nu\beta\beta$ decay. A recent analysis [77, 78] then has shown that the absence of $0\nu\beta\beta$ decay in the Heidelberg-Moscow experiment implied a lower bound on the mass of the excited neutrino, of the order of

$$m_N \geq 3.4m_W \quad (37)$$

for a coupling of order $\mathcal{O}(1)$ and $\Lambda_C \simeq m_N$. Here, m_W is the W-boson mass.

GENIUS in the 1 ton version (10 ton) would allow to improve this limit up to

$$m_N \geq 1.1(2.3)\text{TeV} \quad (38)$$

if $0\nu\beta\beta$ decay is not found.

3.4 GENIUS and Dark Matter

3.4.1 Neutrinos as Hot Dark Matter

As has been already discussed above, if neutrinos have masses in the range of a few eV, they would be good candidates for the hot dark matter in the universe. Of course, from the dark matter argument itself it does not follow which neutrino has to be in this mass range. Clearly, if a neutrino with a sizeable mixing angle to the electron neutrino in this mass range exists, one expects GENIUS to find $0\nu\beta\beta$ decay.

However, if the ν_τ is in the eV range, the ν_e and ν_μ being lighter by at least factors of hundreds and the $\nu_\tau - \nu_e$ mixing angle small at the same time GENIUS with 1 ton would not find double beta decay. In the case of quasi-degenerate models or degenerate models, on the other hand, $0\nu\beta\beta$ decay should be found by GENIUS, unless the CP-phases between the different mass eigenstates take on some special combinations and have a relative minus sign, see the discussion in section 3.1

3.4.2 Cold Dark Matter

Weakly interacting massive particles (WIMPs) are candidates for the cold dark matter in the universe. The favorite WIMP candidate is the lightest supersymmetric particle, presumably the neutralino. The expected detection rates for neutralinos of typically less than one event per day and kg of detector mass [54, 55],

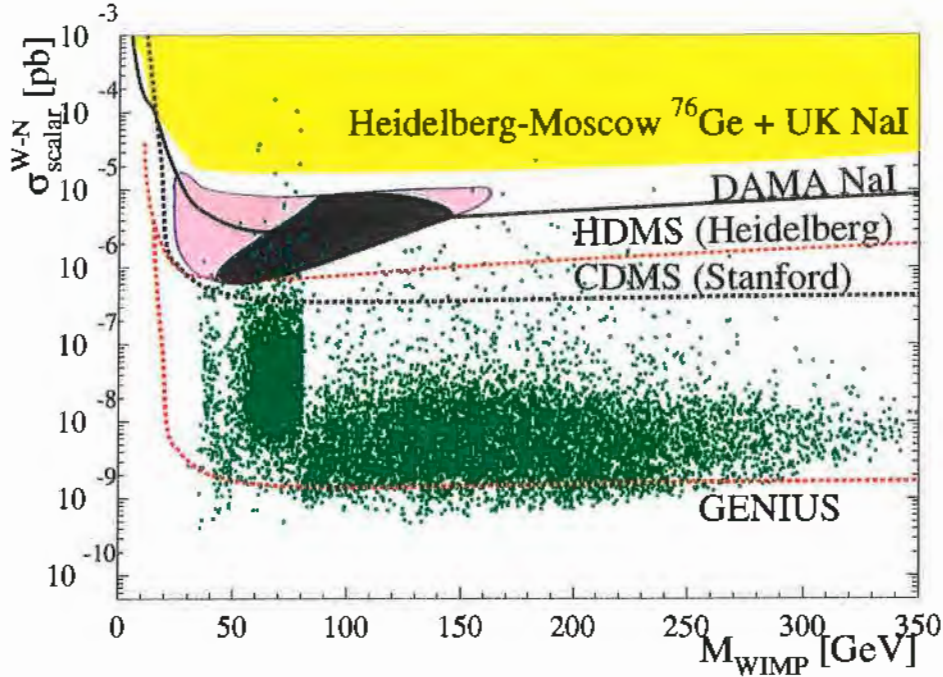


Figure 20: WIMP–nucleon cross section limits (yellow hatched region: excluded by the HEIDELBERG–MOSCOW–Experiment[20] and the UKDMC NaI experiment [79]; solid line: DAMA result for NaI, see [80, 81]) in pb for scalar interactions as function of the WIMP-mass in GeV and of possible results from upcoming experiments (dashed lines for HDMS [82], CDMS [83] and GENIUS). These experimental limits are compared to expectations (scatter plot) for WIMP–neutralino cross sections calculated in the MSSM framework with non-universal scalar mass unification [55]. The 90 % allowed region [84] (light filled area), which is further restricted by indirect dark matter searches [85] (dark filled area), could be easily tested with a 100 kg version of the GENIUS experiment.

however, make direct searches for WIMP scattering experimentally a formidable task.

Fig. 20 shows a comparison of the best existing constraints and future sensitivities of cold dark matter experiments for the scalar WIMP nucleon scattering cross section, together with theoretical expectations for neutralino scattering rates. GENIUS will be the only experiment, which could seriously test the MSSM predictions over the whole SUSY parameter space. In this way, GENIUS, even in a smaller version of 100 kg natural germanium, could compete even with LHC in the search for SUSY, see for example the discussion in [11, 86].

It is interesting to note, that if WIMP scattering is found by GENIUS it could be used to constrain the amount of R-parity violation within supersyn-

metric models. The arguments are very simple. Due to the fact that neutralinos are abundant in the galaxy even today, neutralino decays via R-parity violating operators would have to be highly suppressed.

The details depend, of course, on the neutralino mass and composition. However, finding the neutralino with GENIUS would imply typical limits on R-parity violating couplings of the order of $10^{-(16-20)}$ for any of the λ_{ijk} , λ'_{ijk} or λ''_{ijk} in the superpotential [91]. A positive result of the CDM search at hand, one could thus finally safely conclude that R-parity is conserved.

4 Summary

The GENIUS experiment using enriched ^{76}Ge would be the most sensitive tool to search for neutrinoless double beta decay and cold dark matter (WIMPs). The experiment surpasses the existing neutrino mass experiments by a factor of 50 to 500. The sensitivity for WIMP nucleon scattering is three to four orders of magnitude better than in the existing experiments or those under construction. The shielding and purity requirements were studied using the CERN GEANT Monte Carlo code. Although no requirements beyond those of the latest solar neutrino experiments could be found, of course further studies are needed. The experiment would be small with respect to the costs compared to e.g. detectors in preparation for LHC, like CMS or ATLAS. The required space for the experiment would be available in the Gran Sasso laboratory.

This proposal gives some first discussion on the physics potential of GENIUS, designed to reach $\langle m_\nu \rangle \leq 0.01$ eV with 1 ton and $\langle m_\nu \rangle \leq 0.001$ eV with 10 tons. Besides the neutrino mass, $0\nu\beta\beta$ decay can be used to explore many models beyond the SM. GENIUS would definitely be a breakthrough into the multi-TeV range for many models currently discussed in the literature.

One of the most interesting features of a $0\nu\beta\beta$ decay experiment in the (1–10) meV range is that it might provide very sharp constraints on neutrino oscillation parameters, sharper than those obtainable by other present and future terrestrial experiments. We have discussed several scenarios and analyzed the impact of GENIUS on the corresponding models. A main result is that for all degenerate or quasi-degenerate neutrino mass models a negative result of GENIUS would mean that neutrinos can not be the hot dark matter in the universe.

GENIUS would already in its 1 ton version test the $\nu_e - \nu_\mu$ solution of the atmospheric neutrino problem, in its 10 ton version it could do an independent check of the large angle MSW solution to the solar neutrino problem.

It can be concluded that a $0\nu\beta\beta$ decay experiment probing the neutrino mass down to $\langle m_\nu \rangle \leq (0.01 - 0.001)$ would provide very interesting information, most of which could not be obtained by other experiments.

Besides neutrino masses, GENIUS allows to test also other beyond standard model physics. A prominent example are left-right symmetric models. Here, the sensitivity of GENIUS (1 ton) is already comparable to the one of LHC, while a 10 ton version of GENIUS would be clearly superior to LHC in the search for right-handed W-bosons. For R-parity violating supersymmetry, GENIUS would probe regions in parameter space similar to those tested by the LHC. In addition, GENIUS would allow to improve the leptoquark and compositeness searches by considerable factors.

GENIUS would further have a huge potential for cold dark matter search. By the search for neutralinos it could compete with LHC in the search for supersymmetry. Even if SUSY would be first found at LHC, it would be exciting to test whether neutralinos will show up as dark matter (see [11]). This would also be

the ultimate test for R-parity conservation in supersymmetry.

Thus we conclude, that GENIUS has the ability to provide a major tool for future (astro) particle physics.

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