GENIUS - A New Underground Observatory for Non-Accelerator Particle Physics

H.V. Klapdor–Kleingrothaus

*Max–Planck–Institut für Kernphysik, P.O.Box 10 39 80, D–69029 Heidelberg, Germany

The GENIUS (Germanium in Liquid Nitrogen Underground Setup) project has been proposed in 1997 as first third generation double beta decay project, with a sensitivity aiming down to a level of an effective neutrino mass of \( m_{\nu} \) < 0.01 eV or less. Such sensitivity is important to fix the structure of the neutrino mass matrix with high accuracy, which cannot be done by neutrino oscillation experiments alone. GENIUS will allow broad access also to many other topics of physics beyond the Standard Model of particle physics at the multi-TeV scale. For search of cold dark matter GENIUS will cover a large part of the parameter space of predictions of SUSY for neutralinos as dark matter. Finally, GENIUS has the potential to be a real-time detector for low-energy (pp and \(^7\)Be) solar neutrinos. A GENIUS-Test Facility has just been funded and will come into operation by end of 2002.

1. INTRODUCTION

Without double beta decay there can be no solution of the nature of the neutrino (Dirac or Majorana particle) and of the structure of the neutrino mass matrix. Only investigation of \( \nu \) oscillations and double beta decay together can lead to an absolute mass scale.

Concerning the search for cold dark matter, even a discovery of SUSY by LHC will not have proven that neutralinos form indeed the cold dark matter in the Universe. Direct detection of the latter by underground detectors remains indispensable. Concerning solar neutrino physics, present information on possible \( \nu \) oscillations relies on 0.2% of the solar neutrino flux. The total pp neutrino flux has not been measured and also no real-time information is available for the latter.

The GENIUS project proposed in 1997 (see [1]) as the first third generation \( \beta\beta \) detector, could attack all of these problems with an unprecedented sensitivity.

2. GENIUS, DOUBLE BETA DECAY AND THE LIGHT MAJORANA NEUTRINO MASS

Among present double beta experiments the most sensitive experiment is since eight years the HEIDELBERG-MOSCOW experiment using the world’s largest source strength of 11 kg of 86% enriched \(^{76}\)Ge in form of 5 high-purity Ge detectors, run in the Gran Sasso Underground laboratory. This experiment yields after 53.9 (35.5) kg y of measurement a half-life limit of \( T_{1/2}^{\beta\beta} = 1.3 \times 10^{25} (1.9 \times 10^{25}) \) y \((90\% \, c.l.)\) and an upper limit for the effective neutrino mass \( m_{\nu} \) of 0.42(0.35) eV. The numbers in parentheses are deduced from PSA. These numbers are just entering into the range of expectations for \( m_{\nu} \) from neutrino oscillation experiments (see Fig.2). New approaches and considerably enlarged experiments (as discussed, e.g. in [11]) are required, however, to improve the present accuracy. This can not be done by any of the presently operated double beta experiments, whose status is shown in Fig.4, together with the potential of some future projects under discussion.

With the era of the HEIDELBERG-MOSCOW experiment the time of the small smart experi-
Table lists some key numbers for GENIUS, and of the main other proposals made after the GENIUS proposal. Not all of these proposals fully cover the region to be probed. Since it was realized in the HEIDELBERG-MOSCOW experiment, that the remaining small background is coming from the material close to the detector (holder, copper cap, ...), elimination of any material close to the detector will be decisive. Experiments which do not take this into account, like, e.g. CUORE and MAJORANA, will allow only rather limited steps in sensitivity.

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

In the first proposal for a third generation double beta experiment, the GENIUS proposal, the idea is to use 'naked' Germanium detectors in a huge tank of liquid nitrogen. It has been shown that the detectors show excellent performance under such conditions. GENIUS seems to be at present the only proposal, which can fulfill both requirements mentioned above. The potential of GENIUS is together with that of some later proposals indicated in Fig. 2.

For technical questions and extensive Monte Carlo simulations of the GENIUS project for its various applications we refer to 3.

3. GENIUS AND OTHER BEYOND STANDARD MODEL PHYSICS

GENIUS will also allow 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. 2). 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, sneutrino 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-
Table 1
Some key numbers of future double beta decay experiments (and of the HEIDELBERG-MOSCOW experiment). Explanations: ∇ - assuming the background of the present pilot project. ** - with matrix element from [Sta90*-II], [Tom91**-I], [Hax84**-I], [Wu91*-II], [Wu92*-II] (see Table II in [HM99*-III]), and allowing for an uncertainty of ± 50% of these matrix elements. △ - this case shown to demonstrate the ultimate limit of such experiments. For details see [6].

| ββ Mass | Name         | Status | Mass (tonnes) | Assumed backgr. | Time half-life (y) | Limits for 0νββ | Limits for (mν)(eV) |
|---------|--------------|--------|---------------|----------------|-------------------|----------------|-----------------|
| 76Ge    | HEIDELBERG-MOSCOW [7, 111] | running | 0.011 (enriched) | t 0.06 | 53.9 kg y | 1.3 x 10^25 y, PSA 90% c.l. | 0.42 eV, 0.35 eV PSA 90% c.l. |
| 100Mo   | NEMO III [NEM2000] | under constr. | ~0.01 (enriched) | t 0.0005 | 50 (kg y) | 10^{24}-25 | 0.3-0.7 |
| 130Te   | CUORE V [Gu1998**-VI] | Proposal | 0.75 (nat.) | t 0.5 | 9 - 10^{24} | 0.2-0.5 |
| 130Te   | CUORE | Proposal | 0.75 (nat.) | t 0.005 | 9 - 10^{25} | 0.07-0.2 |
| 100Mo   | MOON [1996**-V1] | idea | 10 (enriched) | ? | 30 (years) | ? | 0.03 |
| 136Xe   | EXO [Dan2000a] | Proposal | 10 | * 0.4 | 8.3 - 10^{46} | 0.05-0.14 |
| 76Ge    | GENIUS [2] | Proposal | 1 (enriched) | t 0.04 - 10^{-3} | 5.8 - 10^{27} | 0.02-0.05 |
| 76Ge    | GENIUS [2] | Proposal | 10 | t 0.15 - 10^{-3} | 2.10^{28} | 0.01-0.028 |

The potential of GENIUS could extend into the multi-TeV region for these fields and its sensitivity would correspond to that of LHC or NLC and beyond (for details see [2]).

4. GENIUS AND COLD DARK MATTER SEARCH

GENIUS would in a first step, with 100 kg of natural Ge detectors, and in three years measuring time, cover a significant part of the MSSM parameter space for prediction of neutralinos as cold dark matter (Fig. 3). For this purpose the background in the energy range < 100 keV has to be reduced to 10^{-2} events/kg y keV, which is possible if the detectors are produced and handled on Earth surface under heavy shielding, to reduce the cosmogenic background produced by spallation through cosmic radiation to a minimum. For details we refer to [2]. Fig. 3 shows together with the expected sensitivity of GENIUS predictions for neutralinos as dark matter by two models, one basing on supergravity and the other on the MSSM, with more relaxed unification conditions.

The sensitivity of GENIUS for Dark Matter with 100 kg of natural Germanium is better than that obtainable with a 1 km^3 AMANDA detector for indirect detection (neutrinos from neutralino annihilation at the Sun). Interestingly both experiments would probe different neutralino compositions: GENIUS mainly gaugino-dominated neutralinos, AMANDA mainly neutralinos with comparable gaugino and Higgsino components. It should be emphasized that, together with DAMA, GENIUS will be the only future Dark Matter experiment, which would be able to positively identify a dark matter signal by the seasonal modulation signature. This cannot be achieved, for example, by the CDMS experiment.
Status and Perspectives of Direct Dark Matter Search

Figure 3. WIMP-nucleon cross section limits in pb for scalar interactions as function of the WIMP mass in GeV. Shown are contour lines of present experimental limits (solid lines) and of projected experiments (dashed lines). Also shown is the region of evidence published by DAMA. The theoretical expectations are shown for the MSSM, by two scatter plots, - for accelerating and for non-accelerating Universe (from [4]), and for MSUGRA, by the grey region (from [8]). Only GENIUS will be able to probe the shown range also by the signature from seasonal modulations.

5. GENIUS AND LOW-ENERGY SOLAR NEUTRINOS

No experiment has separately measured the pp and $^7$Be neutrinos and no experiment has measured the full pp $\nu$ flux. BOREXINO plans to measure $^7$Be neutrinos, the access to pp neutrinos being limited by $^{14}$C contamination (the usual problem of organic scintillators). GENIUS could be the first detector measuring the full pp (and $^7$Be) neutrino flux in real time.

With a radius of GENIUS of 13 m and improving some of the shielding parameters as described in [5], the background can be reduced to a level of $10^{-3}$ events/kg y keV (Fig. 4). This will allow to look for the pp and $^7$Be solar neutrinos by elastic neutrino-electron scattering with a threshold of 11 keV or at most 19 keV (limit of possible tritium background) (Fig. 4), which would be the lowest threshold among other proposals to detect pp neutrinos, such as HERON, HELLAZ, NEON, LENS, MOON, XMASS.

The counting rate of GENIUS (10 ton) would be 6 events per day for pp and 18 per day for $^7$Be neutrinos, i.e. similar to BOREXINO, but by a factor of 30 to 60 larger than a 20 ton LENS detector and a factor of 10 larger than the MOON detector.

6. GENIUS - TEST FACILITY

Construction of a test facility for GENIUS - GENIUS-TF - consisting of $\sim$ 40 kg of HP Ge detectors suspended in a liquid nitrogen box has been started. Up to middle of 2001, six detectors each of $\sim$ 2.5 kg and with a threshold of as low as $\sim$ 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 (Fig. 6). For details we refer to [11].

7. CONCLUSION

The GENIUS project is - among the projected or discussed third generation double beta detectors - the one which may exploit this method to
Figure 5. Simulated spectrum of low-energy solar neutrinos (according to SSM) for the GENIUS detector (1 tonne of natural or enriched Ge) (according to \cite{5,9}).

push the sensitivity on the neutrino mass to the ultimate limit.

GENIUS is the only one of the new projects which simultaneously has a huge potential for cold dark matter search, and for real-time detection of low-energy neutrinos.

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