УДК 539.165

NEW PHYSICS IN THE NEW MILLENNIUM WITH GENIUS: DOUBLE BETA DECAY, DARK MATTER, SOLAR NEUTRINOS

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Double beta decay is indispensable to solve the question of the neutrino mass matrix together with ν oscillation experiments. The most sensitive experiment since eight years — the HEIDELBERG–MOSCOW experiment in Gran Sasso — already now, with the experimental limit of $\langle m_\nu \rangle < 0.26$ eV excludes degenerate ν mass scenarios allowing neutrinos as hot dark matter in the Universe for the small angle MSW solution of the solar neutrino problem. It probes cosmological models including hot dark matter already now on the level of future satellite experiments MAP and PLANCK. It further probes many topics of beyond Standard Model physics at the TeV scale. Future experiments should give access to the multi-TeV range and complement in many ways the search for new physics at future colliders like LHC and NLC. For neutrino physics some of them (GENIUS) will allow one to test almost all neutrino mass scenarios allowed by the present neutrino oscillation experiments. At the same time GENIUS will cover a wide range of the parameter space of predictions of SUSY for neutralinos as cold dark matter. Further, it 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 the end of 2001.

Определение структуры массовой матрицы нейтрино невозможно без двойного бета-распада и экспериментов по поиску нейтринных осцилляций. Наиболее точный эксперимент по бета-распаду коллаборации Гейдельберг–Москва (продолжающийся 8 лет в Гран-Сассо) своим экспериментальным пределом $\langle m_\nu \rangle < 0{,}26$ эВ исключает сценарий с вырожденными массами нейтрино, допускающий нейтрино в качестве горячей темной материи во Вселенной, в случае решения проблемы солнечных нейтрино за счет MSW-механизма при малых углах смешивания нейтрино. Этот эксперимент позволяет получить ограничения на космологические модели горячей темной материи уже сейчас на том уровне точности, который ожидается в планируемых экспериментах на искусственных спутниках MAP и PLANCK. Он также позволяет исследовать различные аспекты физики за рамками стандартной модели в ТэВ-ном масштабе. Будущие эксперименты такого направления должны достигнуть ТэВ-ной области и позволят получить разнообразную дополнительную информацию о новой физике, которую планируется изучать в экспериментах на коллайдерах типа LHC и NLC. В области физики нейтрино некоторые из неускорительных экспериментов (например, GENIUS) дадут возможность исследовать почти все модели генерации нейтринных масс, допускаемые современными осцилляторными экспериментами. В то же время GENIUS позволит исследовать широкую область параметров SUSY, для которых нейтралино представляют собой частицы холодной темной материи. Кроме того, в этом эксперименте можно будет измерять низкоэнергетические ^{7}Be- и pp солнечные нейтрино в реальном времени. Создание тестовой установки GENIUS получило поддержку, и она начнет работать в конце 2001 г.

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INTRODUCTION

Underground physics can complement in many ways the search for New Physics at future colliders, such as LHC and NLC, and can serve as important bridge between the physics that will be gleaned from future high-energy accelerators on the one hand, and satellite experiments such as MAP and PLANCK on the other [3,13,22,15,12,37,30].

The first indication of beyond Standard Model (SM) physics indeed has come from underground experiments (neutrino oscillations from Superkamiokande), and this type of physics will play an even larger role in the future.

Concerning neutrino physics, without double beta decay there will 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 ν oscillations *and* double beta decay together can lead to an absolute mass scale [1–4,23].

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 ν 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 [12,13,3] as the first third-generation $\beta\beta$ detector, could attack all of these problems with an unprecedented sensitivity. In this paper we shall concentrate on the neutrino physics and dark matter aspects. The further potential concerning SUSY, compositeness, leptoquarks, violation of Lorentz invariance and equivalence principle, etc. will only be mentioned briefly and we refer to [37,30,3,15,14].

In section 1 we shall discuss the expectations for the observable of neutrinoless double beta decay, the effective neutrino mass $\langle m_\nu \rangle$, from the most recent ν oscillation experiments, which gives us the required sensitivity for future $0\nu\beta\beta$ experiments. In section 2 we shall discuss the present status and in section 3 the future potential of $0\nu\beta\beta$ experiments.

It will be shown that, if the potential of $0\nu\beta\beta$ decay is exploited to its ultimate experimental limit, it will be possible to test practically all neutrino mass scenarios allowed by the present neutrino oscillation experiments (except for one, the hierarchical LOW solution).

In sections 4 and 5 we shall outline the potential of GENIUS for dark matter search and for real-time detection of low-energy solar neutrinos.

1. ALLOWED RANGES OF $\langle m \rangle$ BY ν OSCILLATION EXPERIMENTS

After the recent results from Superkamiokande (see, e.g., [17,18]), the prospects for a positive signal in $0\nu\beta\beta$ decay have become more promising. The observable of double beta decay $\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2}|m_{ee}^{(2)}| + e^{i\phi_3}|m_{ee}^{(3)}|$, with U_{ei} denoting elements of the neutrino mixing matrix, m_i neutrino mass eigenstates, and ϕ_i relative Majorana CP phases, can be written in terms of oscillation parameters [1,2]:

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

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

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

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

Neutrino oscillation experiments fix or restrict some of the parameters in (1)–(3), e.g., in the case of normal hierarchy solar neutrino experiments yield Δm_{21}^2, $|U_{e1}|^2 = \cos^2\theta_\odot$ and $|U_{e2}|^2 = \sin^2\theta_\odot$. Atmospheric neutrinos fix Δm_{32}^2, and experiments like CHOOZ, looking for ν_e disappearance, restrict $|U_{e3}|^2$. The phases ϕ_i and the mass of the lightest neutrino, m_1, are free parameters. The expectations for $\langle m \rangle$ from oscillation experiments in different neutrino mass scenarios have been carefully analyzed in [1,2]. In sections 1.1 to 1.3 we give some examples.

1.1. Hierarchical Spectrum $(m_1 \ll m_2 \ll m_3)$**.** In hierarchical spectra (Fig. 1), motivated by analogies with the quark sector and the simplest see-saw models, the main contribution

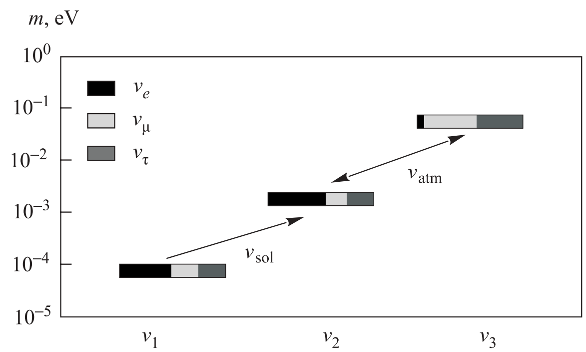

Fig. 1. Neutrino masses and mixings in the scheme with mass hierarchy. Halftone bars correspond to flavor admixtures in the mass eigenstates ν_1, ν_2, ν_3. The quantity $\langle m \rangle$ is determined by the black bars denoting the admixture of the electron neutrino U_{ei}

comes from m_2 or m_3. For the large mixing angle (LMA) MSW solution, which is favored at present for the solar neutrino problem [17], the contribution of m_2 becomes dominant in the expression for $\langle m \rangle$, and

$$\langle m \rangle \simeq m_{ee}^{(2)} = \frac{\tan^2\theta}{1+\tan^2\theta}\sqrt{\Delta m_\odot^2}. \tag{4}$$

In the region allowed at 90 % C.L. by Superkamiokande according to [18], the prediction for $\langle m \rangle$ becomes

$$\langle m \rangle = (1 \div 3) \cdot 10^{-3}\,\text{eV}. \tag{5}$$

The prediction extends to $\langle m \rangle = 10^{-2}$ eV in the 99 % C.L. range (Fig. 2).

1.2. Inverse Hierarchy $(m_3 \approx m_2 \gg m_1)$**.** In inverse hierarchy scenarios (Fig. 3) the heaviest state with the mass m_3 is mainly the electron neutrino, its mass being determined by atmospheric neutrinos, $m_3 \simeq \sqrt{\Delta m_{\text{atm}}^2}$. For the LMA MSW solution one finds [2]

$$\langle m \rangle = (1 \div 7) \cdot 10^{-2}\,\text{eV}. \tag{6}$$

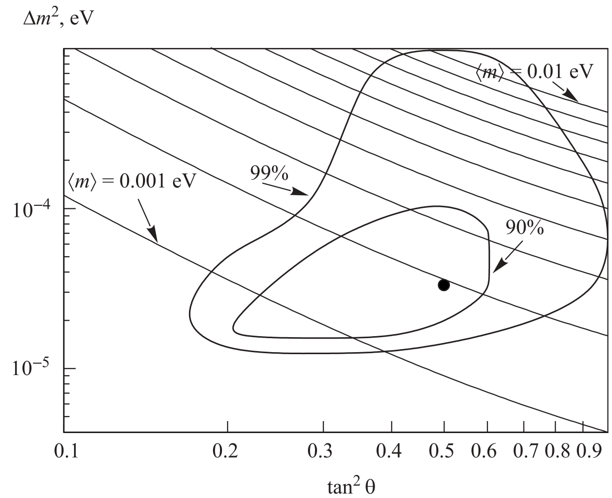

Fig. 2. Double beta decay observable $\langle m \rangle$ and oscillation parameters in the case of the MSW large mixing angle solution of the solar neutrino deficit, where the dominant contribution to $\langle m \rangle$ comes from the second state. Shown are lines of constant $\langle m \rangle$, the lowest line corresponding to $\langle m_\nu \rangle = 0.001$ eV, the upper line to 0.01 eV. The inner and outer closed lines show the regions allowed by present solar neutrino experiments with 90 % C.L. and 99 % C.L., respectively. Double beta decay with sufficient sensitivity could check the LMA MSW solution. Complementary information could be obtained from the search for a day-night effect and spectral distortions in future solar neutrino experiments as well as a disappearance signal in KAMLAND

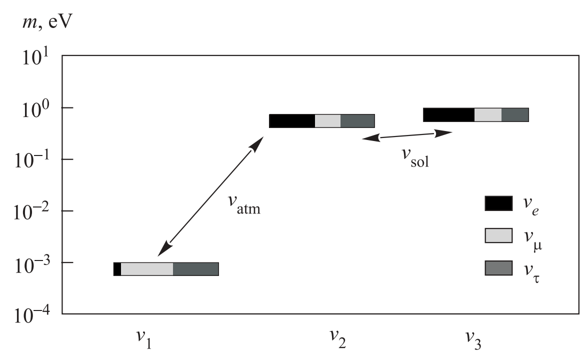

Fig. 3. Neutrino masses and mixing in the inverse hierarchy scenario

1.3. Degenerate Spectrum $(m_1 \simeq m_2 \simeq m_3 \gtrsim 0.1$ eV$)$. Since the contribution of m_3 is strongly restricted by CHOOZ, the main contribution comes from m_1 and m_2, depending on their admixture to the electron flavors, which is determined by the solar neutrino solution. We find [2]

$$m_{\min} < \langle m \rangle < m_1 \qquad \text{with} \qquad \langle m_{\min} \rangle = (\cos^2\theta_\odot - \sin^2\theta_\odot)\, m_1. \tag{7}$$

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

After these examples we give a summary of our analysis [1,2] of the $\langle m \rangle$ allowed by ν oscillation experiments for neutrino mass models in the presently favored scenarios (Fig. 4). The size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases.

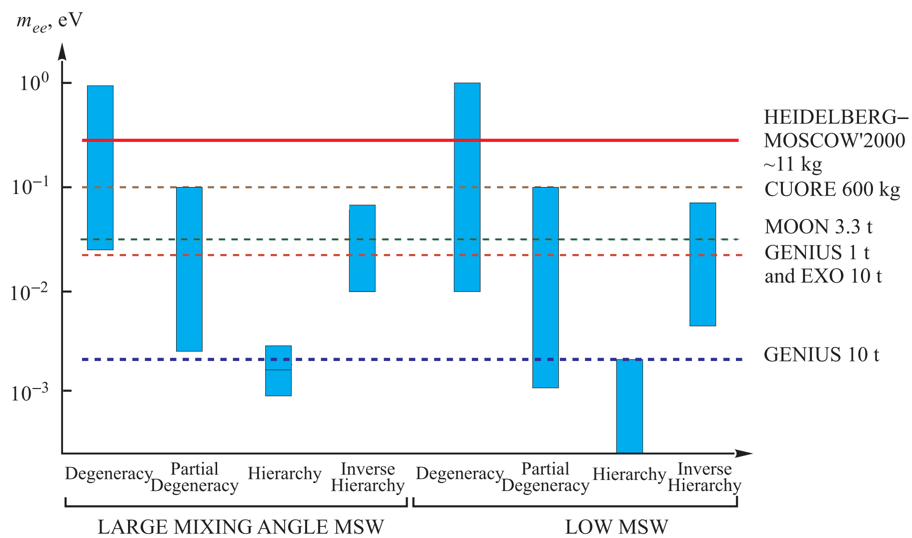

Fig. 4. Summary of values for $m_{ee} = \langle m \rangle$ expected from neutrino oscillation experiments (status NEUTRINO'2000), in the different schemes discussed in this paper. For a more general analysis see [1]. The expectations are compared with the recent neutrino mass limits obtained from the HEIDELBERG–MOSCOW experiment [7,19], as well as the expected sensitivities for the CUORE [50], MOON [47], EXO [48] proposals and the 1 tonne and 10 tonne proposal of GENIUS [12,13]

2. STATUS OF $\beta\beta$ EXPERIMENTS

The status of present double beta experiments is shown in Fig. 5 and is extensively discussed in [3]. The HEIDELBERG–MOSCOW experiment, using the largest source strength of 11 kg of enriched ^{76}Ge in form of five HP Ge detectors in the Gran Sasso underground laboratory [3,35], yields after a time of 37.2 kg·y of measurement (Fig. 6) a half-life limit [19,20]

$$T_{1/2}^{0\nu} > 2.1(3.5) \cdot 10^{25} \text{ y}, \quad 90\,\% \ (68\,\%) \text{ C.L.},$$

and a limit for the effective neutrino mass

$$\langle m \rangle < 0.34(0.26) \text{ eV}, \quad 90\,\% \ (68\,\%) \text{ C.L.}$$

This sensitivity just starts to probe some (degenerate) neutrino mass models (see Fig. 4). In degenerate models from the experimental limit on $\langle m \rangle$ we can derive an upper bound on the mass scale of the heaviest neutrino. For the LMA solar solution we obtain from (7)

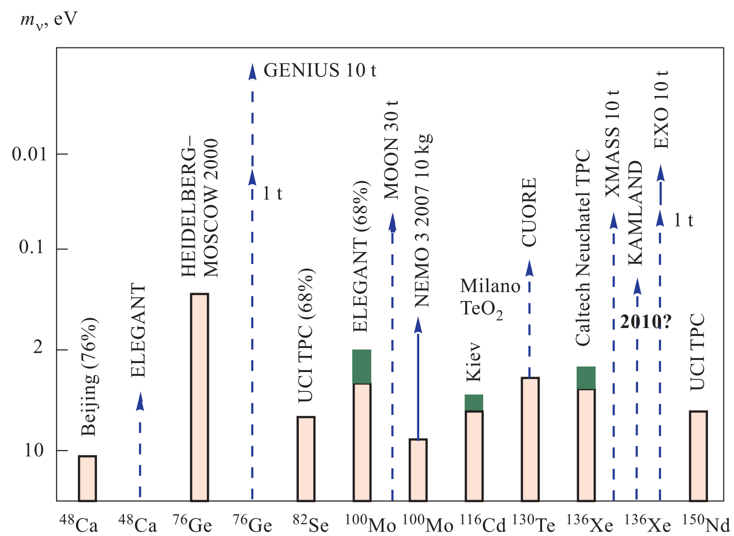

Fig. 5. Present situation, 2000, and expectation for the future of the most promising $\beta\beta$ experiments. Light parts of the bars — present status; dark parts — expectation for running experiments; solid and dashed lines — experiments under construction and proposed experiments. For references see [3,39,65]

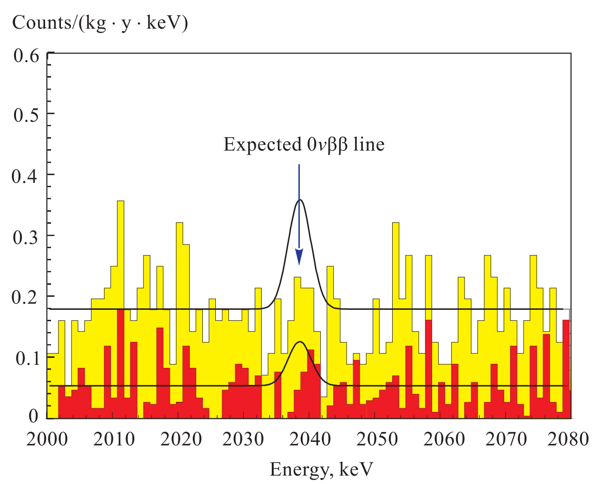

Fig. 6. HEIDELBERG–MOSCOW experiment: energy spectrum in the range between 2000 and 2080 keV, where the peak from neutrinoless double beta decay is expected. The open histogram denotes the overall sum spectrum without PSA after 55.9 kg·y of measurement (since 1992). The filled histogram corresponds to the SSE data after 37.2 kg·y. Also shown are the excluded (90 % C.L.) peak areas from the two spectra

$m_{1,2,3} < 1.1$ eV implying $\sum m_i < 3.2$ eV. This first number is sharper than what has recently been deduced from single beta decay of tritium ($m < 2.2$ eV [28]), and the second is sharper than the limit of $\sum m_i < 5.5$ eV still compatible with most recent fits of Cosmic Microwave Background Radiation and Large Scale Structure data (see, e.g., [29]).

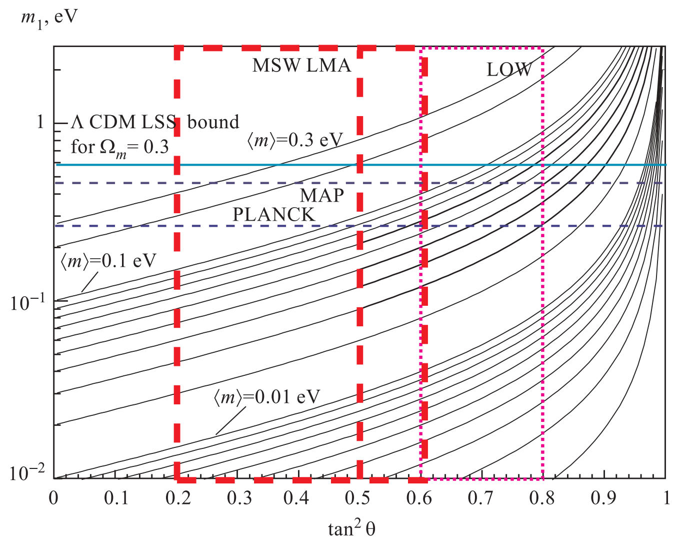

Fig. 7. Double beta decay observable $\langle m \rangle$ and oscillation parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses m_0 and mixing $\tan^2 2\theta_{12}$. Also shown are a cosmological bound deduced from a fit of CMB and large scale structure [16] and the expected sensitivity of the satellite experiments MAP and PLANCK. The present limit from tritium β decay of 2.2 eV [28] would lie near the top of the figure. The range of $\langle m \rangle$ investigated at present by the HEIDELBERG–MOSCOW experiment is, in the case of small solar neutrino mixing, already in the range to be explored by MAP and PLANCK [16]

The result has found a large resonance, and it has been shown that it excludes, for example, the small angle MSW solution of the solar neutrino problem in degenerate scenarios, if neutrinos are considered as hot dark matter in the Universe [24–27]. Figure 7 shows that the present sensitivity probes cosmological models including hot dark matter already now on a level of the future satellite experiments MAP and PLANCK.

The HEIDELBERG–MOSCOW experiment, using the world's largest source strength, yields now, since eight years, by far the sharpest limits worldwide. If future searches show that $\langle m \rangle > 0.1$ eV, then the three-ν mass schemes, which will survive, are those with ν mass degeneracy or 4-neutrino schemes with inverse mass hierarchy (Fig. 4 and [1]).

It has been discussed in detail earlier (see, e.g., [3,12,14,22]) that none of the present-generation experiments has a potential to probe $\langle m \rangle$ below the present HEIDELBERG–MOSCOW level (see Fig. 5).

A second experiment using enriched ^{76}Ge, IGEX, stopped operation by the end of 1999 [59]. This experiment started in 1992 with 2.1 kg of ^{76}Ge [63] and operated in 1995 already 8 kg of ^{76}Ge [62]. In 1999 they published a measuring time of 5.7 kg·y (less than one year of full operation) [60,61], and in autumn 1999 of about 9 kg·y [58] (less than one quarter of the HEIDELBERG–MOSCOW significance) and an optimistic value for $\langle m \rangle$, using a method criticized.

The Milano cryogenic experiment using TeO_2 bolometers improved their values for the $\langle m_\nu \rangle$, from $\beta\beta$ decay of ^{130}Te from 5.3 eV in 1994 [52] to 1.8 eV in 2000 [53], and according to [51] to 0.9 eV in 2001.

Also CUORICINO (with 45 kg of detectors), scheduled for starting in autumn 2001 [51], will hardly reach the HEIDELBERG–MOSCOW limit (see also discussion in [73]).

NEMO-III, originally aiming at a sensitivity of 0.1 eV, reduced their goals recently to $0.3 \div 0.7$ eV [56] (which is more consistent with estimates given by [55]) to be reached in 6 years from starting of running, foreseen for the year 2002.

3. THE FUTURE OF $\beta\beta$ EXPERIMENTS

To extend the present sensitivity of $\beta\beta$ experiments below a limit of 0.1 eV requires completely new experimental approaches, as discussed extensively in [3,12–14].

Figure 4 shows that an improvement of the sensitivity down to $\langle m \rangle \sim 10^{-3}$ eV is required to probe all neutrino mass scenarios allowed by present neutrino oscillation experiments [12,1]. With this result of ν oscillation experiments, nature seems to be generous to us since such a sensitivity seems to be achievable in future $\beta\beta$ experiment, if this method is exploited to its ultimate limit [3,12,13].

3.1. GENIUS, Double Beta Decay and the Light Majorana Neutrino Mass. With the era of the HEIDELBERG–MOSCOW experiment, which will remain the most sensitive experiment in the next years, the time of small smart experiments is over.

The requirements for sensitivity in future experiments to play a decisive role in the solution of the structure of the neutrino mass matrix can be read from Fig. 4.

To reach the required level of sensitivity, $\beta\beta$ experiments have to become large. On the other hand, source strengths of up to 10 tons of enriched material touch the world production limits. At the same time the background has to be reduced by a factor of 1000 and more as compared to that of the HEIDELBERG–MOSCOW experiment.

The table lists some key numbers for GENIUS, which was the first proposal for a third-generation double beta experiment and which may be *the only* project that will be able to test *all* neutrino mass scenarios, and for the main other proposals made *after* the GENIUS proposal. Their potential is shown also in Fig. 4. It is seen that not all of these proposals fully cover the region to be probed. Among them is also the recently presented MAJORANA project [64], which does not really apply any new strategy for background reduction.

The CAMEO project [73] will have to work on *very* long time scales, since it has to wait for the end of the BOREXINO solar neutrino experiment.

CUORE [54] still has, with the complexity of cryogenic techniques, to overcome serious problems of background to enter into interesting regions of $\langle m_\nu \rangle$.

EXO [48] needs still very extensive research and development to probe the applicability of the proposed detection method.

In the GENIUS project a reduction by a factor of more than 1000 down to a background level of 0.1 events/(t·y·keV) in the range of $0\nu\beta\beta$ is reached by removing all material close to the detectors, and by using naked germanium detectors in a large tank of liquid nitrogen. It has been shown that the detectors demonstrate excellent performance under such conditions [13,12].

For technical questions and extensive Monte Carlo simulations of the GENIUS project for its application in double beta decay we refer to [13,34].

Some key numbers of future double beta decay epxeriments and of the HEIDELBERG–MOSCOW experiment

$\beta\beta$ isotope	Name of experiment	Status	Mass, t	Assumed background, $\dagger\,\frac{\text{events}}{\text{kg}\cdot\text{y}\cdot\text{keV}}$, $\ddagger\,\frac{\text{events}}{\text{kg}\cdot\text{y}\cdot\text{FWHM}}$, $*\,\frac{\text{events}}{\text{y}\cdot\text{FWHM}}$	Running time, $t \cdot y$	Results limit for $0\nu\beta\beta$ half-life, y	$\langle m_\nu \rangle$, eV
^{76}Ge	HEIDELBERG–MOSCOW [7,19,37]	running since 1990	0.011 (enriched)	† 0.06 ‡ 0.24 * 2	37.24 kg · y	$2.1 \cdot 10^{25}$ 90 % C.L. $3.5 \cdot 10^{25}$ 68 % C.L. NOW !!	< 0.34 ** 90 % C.L. < 0.26 ** 68 % C.L. NOW !!
^{100}Mo	NEMO III [56]	under construction end 2001?	~ 0.011 (enriched)	† 0.0005 ‡ 0.2 * 2	50 kg · y	10^{24}	0.3–0.7
^{130}Te	CUORE$^{\bigtriangledown}$ [54]	idea since 1998	0.75 (natural)	† 0.5 ‡ 4.5 * 1000	5	$9 \cdot 10^{24}$	0.2–0.5
^{130}Te	CUORE [54, 57]	idea since 1998	0.75 (natural)	† 0.005 ‡ 0.045 *45	5	$9 \cdot 10^{25}$	0.07–0.2
^{100}Mo	MOON [47, 65]	idea since 1999	10 (enrich.) 100 (nat.)	?	30 300	?	0.03
^{116}Cd	CAMEO II CAMEO III [73]	idea since 2000	0.65 1 (enrich.)	* 3 ?	5–8 5–8	10^{26} 10^{27}	0.06 0.02
^{136}Xe	EXO [48, 49]	Proposal since 1999	1 10	* 0.4 * 0.6	5 10	$8.3 \cdot 10^{26}$ $1.3 \cdot 10^{28}$	0.05–0.14 0.01–0.04
^{76}Ge	GENIUS-TF [40, 41]	under construction end 2001?	11 kg (enrich.)	† $6 \cdot 10^{-3}$	3	$1.6 \cdot 10^{26}$	0.15
^{76}Ge	GENIUS [12, 13]	Proposal since 1997	1 (enrich.) 1	‡ $0.04 \cdot 10^{-3}$ ‡ $0.15 \cdot 10^{-3}$ * 0.15 * 1.5	1 10	$5.8 \cdot 10^{27}$ $2 \cdot 10^{28}$	0.02–0.05 0.01–0.028
^{76}Ge	GENIUS [12, 13]	Proposal since 1997	10 (enrich.)	‡ $0.15 \cdot 10^{-3}$ $0^{\triangle}$	10 10	$6 \cdot 10^{28}$ $5.7 \cdot 10^{29}$	0.006–0.016 0.002–0.0056

$\bigtriangledown$ — assuming the background of the present pilot project; $**$ — with matrix element from [42–46] (see Table II in [21]); $\triangle$ — this case is shown to demonstrate the ultimate limit of such experiments.
For details see [3].

3.2. GENIUS and Other Beyond Standard Model Physics. GENIUS will allow, besides the major step in neutrino physics described above, the access to a broad range of other beyond SM physics topics in the multi-TeV range. Already now $\beta\beta$ decay probes the TeV scale on which new physics should manifest itself (see, e.g., [12,36]). Based to a large extent on the theoretical work of the Heidelberg group in the last five years, the HEIDELBERG–MOSCOW experiment yields results for SUSY models (R-parity breaking, neutrino mass), leptoquarks (leptoquarks-Higgs coupling), compositeness, right-handed W mass, nonconservation of Lorentz invariance and equivalence principle, mass of a heavy left- or right-handed neutrino, competitive to corresponding results from high-energy accelerators like TEVATRON and HERA. The potential of GENIUS extends into the multi-TeV region for these fields and its sensitivity would correspond to that of LHC or NLC and beyond (for details see [3,36]).

4. GENIUS AND COLD DARK MATTER SEARCH

Already now the HEIDELBERG–MOSCOW experiment is the most sensitive Dark Matter experiment worldwide concerning the raw data [9,8,10,11]. GENIUS would already in a first

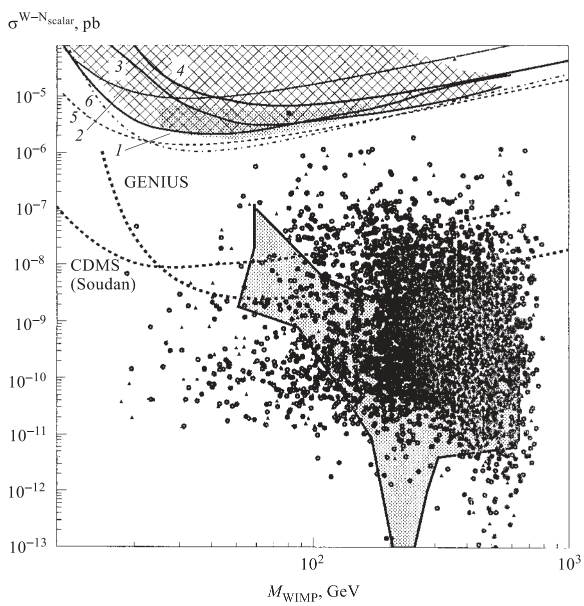

Fig. 8. WIMP-nucleon cross section limits in pb for scalar interactions as function of the WIMP mass in GeV. Shown are contour lines of present experimental limits (solid lines: *1* — CDMS, *2* — HDMS prototype, *3* — DAMA NAT, *4* — HEIDELBERG–MOSCOW ^{76}Ge) and of projected experiments (dashed lines: *5* — HDMS projection, *6* — GENIUS-TF projection — 4 keV threshold with NAT2). Also presented is the region of evidence published by DAMA. The theoretical expectations are shown by a scatter plot (from [32]) and by grey region (from [38]). *Only* GENIUS will be able to probe the shown range also by the signature from seasonal modulations

step, with 100 kg of natural Ge detectors, cover a significant part of the MSSM parameter space for prediction of neutralinos as cold dark matter (Fig. 8) (see, e.g., [31]). For this purpose the background in the energy range < 100 keV has to be reduced to 10^{-2} events/(kg·y·eV), which is possible if the detectors are produced and handled on the Earth surface under heavy shielding, to reduce the cosmogenic background produced by spallation through cosmic radiation (critical products are tritium, ^{68}Ge, ^{63}Ni, ...) to a minimum. For details we refer to [13]. Figure 8 shows, together with the expected sensitivity of GENIUS, predictions for neutralinos as dark matter by two models, one based on supergravity [38], the other starting from more relaxed unification conditions [32].

The sensitivity of GENIUS for Dark Matter corresponds to that obtainable with a 1-km^3 AMANDA detector for indirect detection (neutrinos from annihilation of neutralinos captured at the Sun) (Fig. 9) [69]. Interestingly, both experiments would probe different neutralino compositions: GENIUS mainly gaugino-dominated neutralinos, AMANDA mainly neutralinos with comparable gaugino and Higgsino components (see Fig. 38 in [69]). It should be stressed that, together with DAMA, the GENIUS experiment will be *the only* future Dark Matter experiment that 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.

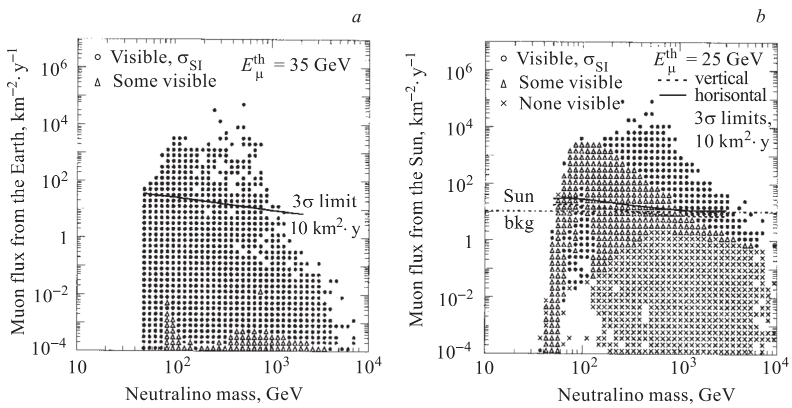

Fig. 9. Sensitivity of future AMANDA 1 km^3 for indirect detection of dark matter and of GENIUS for direct detection of dark matter. AMANDA looks for muons from neutrino produced by neutralino annihilation, and can exclude (probe) the range beyond the total time. GENIUS looks for nuclear recoils from neutralino scattering. It can probe (*a*) the light shaded area, i.e., is much more sensitive than AMANDA for neutrinos from the Earth, and (*b*) the upper and middle light, as well as partly the dark areas, i.e., is of similar sensitivity as AMANDA for neutrinos from the Sun (from [69])

5. GENIUS AND LOW-ENERGY SOLAR NEUTRINOS

GALLEX and SAGE measure $pp+\,^7\mathrm{Be}+\,^8\mathrm{B}$ neutrinos $(60+30+10\,\%)$ down to 0.24 MeV, the Chlorine experiment measured $^7\mathrm{Be}+\,^8\mathrm{B}$ neutrinos (80 % ^{8}B) above $E_\nu = 0.817$ MeV, all without spectral, time and detection information. No experiment has separately measured the pp and ^{7}Be neutrinos and no experiment has measured the *full pp* ν flux. BOREXINO plans to measure ^{7}Be neutrinos, with access to *pp* neutrinos being limited by ^{14}C contamination (the usual problem of organic scintillators). GENIUS could be the first detector to measure the *full pp* (and ^{7}Be) neutrino flux in real time.

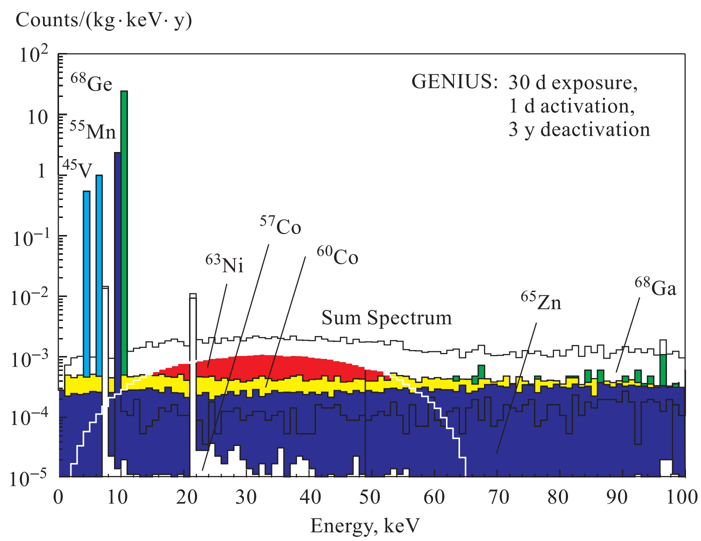

Fig. 10. Simulated cosmogenic background during detector production. Assumptions: 30-day exposure of material before processing, 1-day activation after zone refining, 3-year deactivation underground (see [7,39])

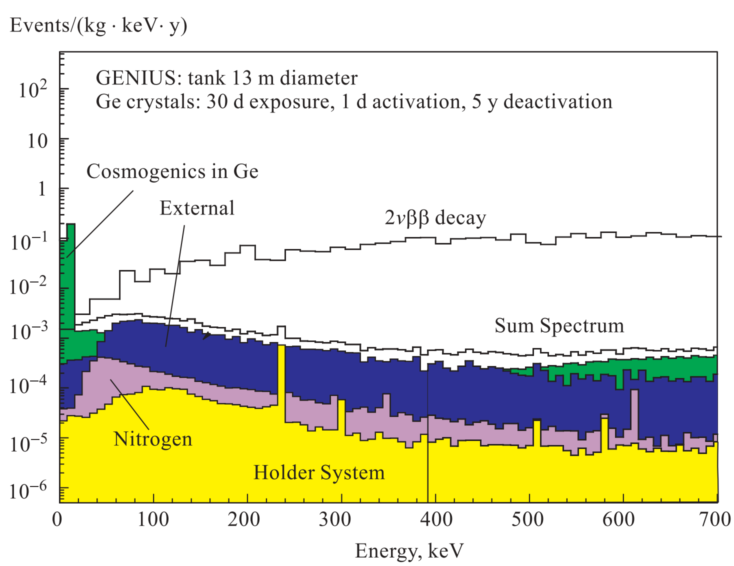

Fig. 11. Total background in a 13 m liquid nitrogen tank for detectors produced as described in Fig. 10 (see [7,39])

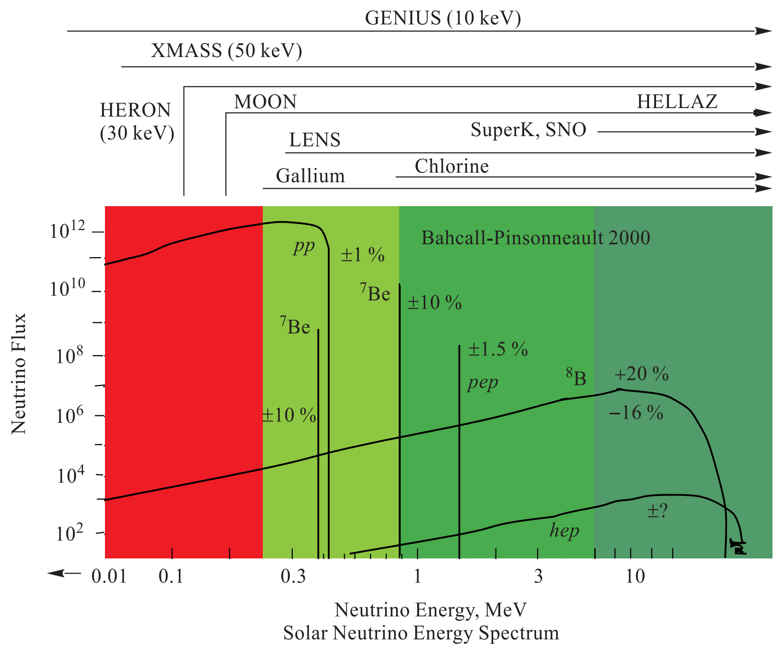

Fig. 12. The sensitivity (thresholds) of different running and projected solar neutrino detectors (see [68] and HEIDELBERG–MOSCOW home-page: http://www.mpi-hd.mpg.de/non_acc/)

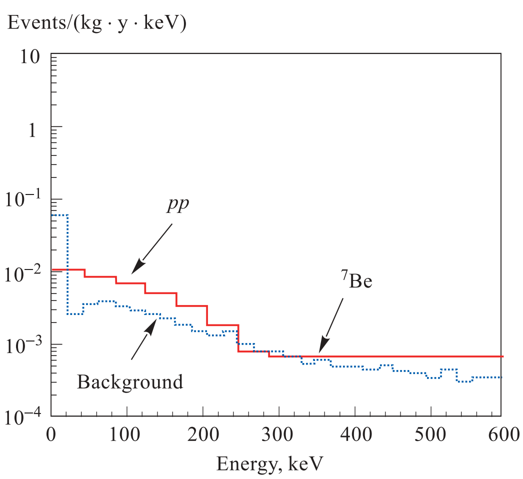

Fig. 13. Simulated spectrum of low-energy solar neutrinos (according to SSM) for the GENIUS detector (1 tonne of natural or enriched Ge) (from [6])

Extending the radius of GENIUS to 13 m and improving some of the shielding parameters as described in [6,13], the background can be reduced to a level of 10^{-3} events/(kg·y·keV) (see also [5]). Figure 10 shows the simulated background from the cosmogenics produced during detector production, assuming 30 days of exposure to cosmic rays of the material between mining and zone refining, 1 day of exposure during and after zone refining, and 3 years of deactivation of the detectors underground. Figure 11 shows the total background expected under these production conditions. This background will allow one 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) (Figs. 12, 13) which would be the lowest threshold among other proposals to detect *pp* neutrinos, such as HERON [65], HELLAZ [65], NEON [65], LENS [67,65], MOON [47,65], XMASS [66,65].

	Water	^{37}Cl	^{71}Ga	D_2O	^{176}Yb	^{76}Ge	Scintill.	Drift chamb.
Thre-shold, MeV	5	0.817	0.235	1.4 (CC) 2.2 (NC) 0 (elast.)	0.241 0.301	0.011	~ 0.030 0.050 or 0.352	0.100 0.168
Resolu-tion, %, keV					100	0.3 % at 300 keV	not good (compt. edge)	5 % 7 %
Mass, t	50000	615 C_2Cl_4	30 + 57	1000	10–30 enr. (8 %)	1–10	100 1000 10 10	2000 m^3 3.3
Reac-tions	γ-rays	$^{37}Ar \to {}^{37}Cl$ $+e+\tilde{\nu}_e$	$^{71}Ga + \tilde{\nu}_e \to$ $^{71}Ge + e$	$\nu_e + d \to$ $p+p+e$, $\nu_x + d \to$ $n+p+\nu_x$	$^{176}Yb + \nu_e$ $\to {}^{176}Lu$	$\nu + e^- \to$ $\nu + e^-$	$\nu + e^- \to$ $\nu + e^-$	$\nu_e + e^- \to$ $\nu_e + e^-$
Names of experi-ments	Super-kamio-kande (scatter.)	Davis Exper. (absorpt.)	GALLEX (GNO) SAGE (absorpt.)	SNO (scatter.)	LENS (absorpt.)	GENIUS (scatter.)	BOREXINO Kamland HERON XMASS (scatter.)	HELLAZ (scatter.) MOON (absorpt.)
Sensitivity, %, events/d: ^{7}Be	—	20 %, 1 d^{-1}	30 %, 1 d^{-1}	—	~ 0.2 d^{-1}	33 %, 0.6–6 d^{-1}	6 d^{-1}	4 %, 0.4 d^{-1}
^{8}B	100 %, 20–30 d^{-1}	80 %, 1 d^{-1}	10 %, 1 d^{-1}	100 %				
pp	—	—	60 %, 1 d^{-1}	—	~ 0.3 d^{-1}	66 %, 1.8–18 d^{-1}	14 d^{-1}	7 %, 1.1 d^{-1}

Fig. 14. Some key numbers of running and future solar neutrino experiments (see also [39])

The counting rate of GENIUS (10 ton) would be 6 events per day for *pp* and 18 events 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 by a factor of 10 larger than the MOON detector (see Fig. 14).

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. By the end of January 2001, four detectors each of $\sim$ 2.5 kg and with a threshold as low as $\sim$ 500 eV have been produced.

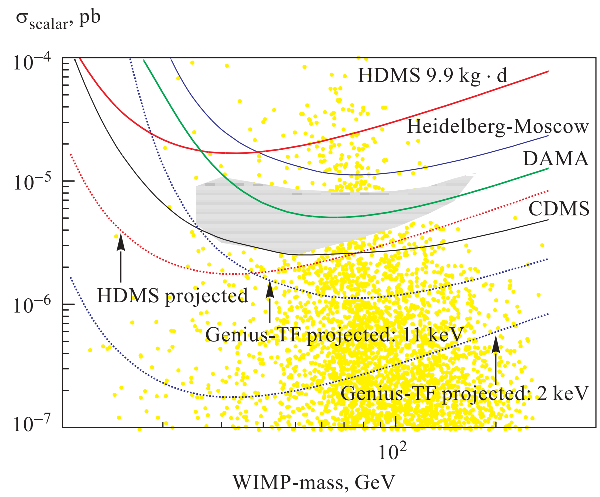

Fig. 15. WIMP-nucleon cross section limits as a function of the WIMP mass for spin-independent interactions. The solid lines are current limits of the HEIDELBERG–MOSCOW experiment [8], the HDMS prototype [9], the DAMA experiment [70] and the CDMS experiment [72]. The dashed curves are the expectation for HDMS [9] and for GENIUS-TF with an energy threshold of 11 and 2 keV respectively, and a background index of 2 events/(kg·y·keV) below 50 keV. The filled contour represents the 2σ evidence region of the DAMA experiment [71]. The experimental limits are compared to expectations (scatter plot) for WIMP-neutralinos calculated in the MSSM parameter space under the assumption that all superpartner masses are lower than 300–400 GeV [33] (from [40,41]).

Besides test of various parameters of the GENIUS project, the test facility would allow one, 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 within about one year of measurement with 95 % C.L. Even for an initial lower mass of 20 kg the time scale would be not larger than three years (Fig. 15) (for details see [40,41]). Using the enriched ^{76}Ge detectors of the HEIDELBERG–MOSCOW experiment in the GENIUS-TF setup, a background in the $0\nu\beta\beta$ region by a factor of 30 smaller than that in the HEIDELBERG–MOSCOW experiment could be obtained, which would allow one to test the effective Majorana neutrino mass down to 0.15 eV (90 % C.L.) in 6 years of measurement (Fig. 16). This limit is similar to what much larger experiments aim at (see the table).

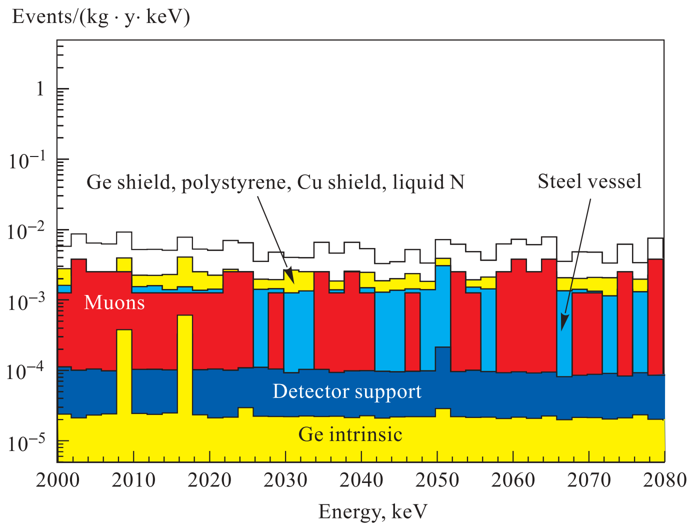

Fig. 16. Simulated spectra of the dominant background sources for the enriched ^{76}Ge detectors of the HEIDELBERG–MOSCOW experiment in the GENIUS-TF setup. The energy region relevant for the search of the neutrinoless double beta decay is shown. The upper solid line represents the sum spectrum of all the simulated components (from [40,41])

CONCLUSION

The GENIUS project is — among the other projected or discussed third-generation double beta detectors — the one which exploits this method to obtain information on the neutrino mass to the ultimate limit. Nature is extremely generous to us, so that with an increase of the sensitivity by two orders of magnitude compared to the present limit, down to $\langle m_\nu \rangle < 10^{-3}$ eV, indeed essentially all the neutrino scenarios allowed by present neutrino oscillation experiments can be probed.

GENIUS is the only of the new projects (Fig. 17) that simultaneously has a huge potential for cold dark matter search, and for real-time detection of low-energy neutrinos.

			Potential for:	
	Backgr. reduct.	Mass increase	Dark matter	Solar neutrinos
GENIUS	+	+	+	+*)
CUORE	(+)	+	–	–
MOON	(+)	+	–	+
EXO	+	+	–	–
MAJORANA	–	+	–	–

*) real time measurement of *pp* neutrinos with a threshold of 10 keV (!!)

Fig. 17. New projects under discussion for future double beta decay experiments (see [3])

REFERENCES

1. *Klapdor-Kleingrothaus H.V., Pas H., Smirnov A.Yu.* // Phys. Rev. D. 2000; Preprint hep-ph/0003219. 2000.
2. *Klapdor-Kleingrothaus H.V., Pas H., Smirnov A.Yu.* // Proc. of DARK2000, Heidelberg, Germany, July 10–15, 2000 / Ed. H.V.Klapdor-Kleingrothaus. Heidelberg, 2001.

3. *Klapdor-Kleingrothaus H.V.* 60 Years of Double Beta Decay. Singapore: World Scientific, 2001. 1253 p.
4. *Klapdor-Kleingrothaus H.V., Pas H.* Preprint physics/0006024; Commun. in «Nucl. Part. Phys.» 2000.
5. *Klapdor-Kleingrothaus H.V.* // Proc. of Intern. Workshop on Low Energy Solar Neutrinos (LowNu2), Tokyo, Japan, December 4–5, 2000 / Ed. Y.Suzuki. Singapore, 2001.
6. *Baudis L., Klapdor-Kleingrothaus H.V.* // Eur. Phys. J. A. 1999. V.5 P.441–443.
7. *Klapdor-Kleingrothaus H.V. et al.* To be publ. in 2001 and http://www.mpi-hd.mpg.de/non-acc/main.html.
8. HEIDELBERG–MOSCOW Collaboration // Phys. Rev. D. 1998. V.59. P.022001.
9. *Baudis L. et al.* // Phys. Rev. D. 2001. V.63. P.22001; astro-ph/0008339.
10. *Ramachers Y.* for the CRESST Collaboration // Proc. of XI Rencontres de Blois, Frontiers of Matter, France, June 27 – July 3, 1999.
11. *Klapdor-Kleingrothaus H.V., Majorovits B.* // Proc. of Third Intern. Conf. on Dark Matter in Astro and Particle Physics (DARK2000), Heidelberg, Germany, July 10–15, 2000 / Ed. H.V.Klapdor-Kleingrothaus. Heidelberg, 2001.
12. *Klapdor-Kleingrothaus H.V.* // Proc. of the First Intern. Conf. on Particle Physics Beyond the Standard Model (BEYOND'97), Castle Ringberg, Germany, June 8–14, 1997 / Eds. H.V.Klapdor-Kleingrothaus, H.Pas. Bristol, 1998. P.485–531; Intern. J. Mod. Phys. A. 1998. V.13. P.3953; J. Phys. G. 1998. V.24 P.483–516.
13. *Klapdor-Kleingrothaus H.V. et al.* MPI-Report MPI-H-V26-1999; Preprint hep-ph/9910205; Proc. of the 2nd Intern. Conf. on Particle Physics Beyond the Standard Model (BEYOND'99), Castle Ringberg, Germany, June 6–12, 1999 / Ed. by H.V.Klapdor-Kleingrothaus, I.V.Krivosheina. Bristol, 2000. P.915–1014.
14. *Klapdor-Kleingrothaus H.V.* // Proc. of 18th Intern. Conf. on Neutrino Physics and Astrophysics (NEUTRINO 98), Takayma, Japan, June 4–9, 1998 / Ed. Y.Suzuki et al.; Nucl. Phys. Proc. Suppl. 1999. V.77. P.357–368.
15. *Klapdor-Kleingrothaus H.V.* // Proc. of 5th Intern. Conf. «Physics Beyond the Standard Model» (WEIN'98) / Ed. P.Herczeg, C.M.Hoffman, H.V.Klapdor-Kleingrothaus. Singapore, 1999. P.275–311.
16. *Lopez R.E.* astro-ph/9909414;
Primack J.R., Gross M.A.K. astro-ph/0007165;
Primack J.R. astro-ph/0007187;
Einasto J. // Proc. of DARK2000, Heidelberg, Germany, July 10–15, 2000. / Ed. H.V.Klapdor-Kleingrothaus. Heidelberg, 2001.
17. *Suzuki Y.* // Proc. of NEUTRINO'2000, Sudbury, Canada, June 2000 / Ed. A.B.McDonald et al. 2001.
18. *Gonzalez-Garcia M.C. et al.* hep-ph/0009350; Phys. Rev. D. 2001. V.63. P.033005.
19. *Klapdor-Kleingrothaus H.V. et al.* // Annual Report Gran Sasso 2000. 2001.
20. *Klapdor-Kleingrothaus H.V. et al.* // MPI Heidelberg, Annual Report 1999–2000. 2001.
21. HEIDELBERG–MOSCOW Coll. // Phys. Rev. Lett. 1999. V.83. P.41–44.
22. *Klapdor-Kleingrothaus H.V.* // Proc. of Conf. «Origins of Neutrino Oscillations» (NOW'2000) / Ed. G.Fogli; to appear in «Nucl. Phys. B», 2001.

23. *Klapdor-Kleingrothaus H.V.* // Proc. of Intern. Workshop on «Neutrino Oscillations and Their Origin» (NOON'2000), Tokyo, Japan, Dec. 2000. Singapore, 2001.
24. *Georgi H., Glashow S.L.* // Phys. Rev. D. 2000. V.61. P.097301.
25. *Minakata H., Yasuda O.* // Phys. Rev. D. 1997. V.56. P.1692;
Minakata H. hep-ph/0004249.
26. *Yasuda O.* // Proc. of Beyond the Desert'99 / Ed. by H.V.Klapdor-Kleingrothaus, I.V.Krivosheina. Bristol, 2000. P.223.
27. *Ellis J., Lola S.* // Phys. Lett. B. 1999. V.458. P.310; Preprint hep-ph/9904279.
28. *Weinheimer C.* // Proc. of NEUTRINO'2000, Sudbury, Canada, June 16–21, 2000 / Ed. A.B.McDonald et al. 2001.
29. *Tegmark M., Zaldarriaga M., Hamilton A.J.S.* Preprint hep-ph/0008145.
30. *Klapdor-Kleingrothaus H.V.* // Int. J. Mod. Phys. A. 1998. V.13. P.3953; J. Phys. G. 1998. V.24. P.483–516.
31. *Klapdor-Kleingrothaus H.V., Ramachers Y.* // Eur. Phys. J. A. 1998. V.3. P.85–92.
32. *Bednyakov V.A., Klapdor-Kleingrothaus H.V.* // Phys. Rev. D. 2000. V.62. P.043524/1-9; Preprint hep-ph/0011233. 2000. In press in «Phys. Rev. D». 2001.
33. *Bednyakov V.A., Klapdor-Kleingrothaus H.V.* // Phys. Rev. D. 2000. V.62. P.043524; hep-ph/9908427.
34. *Klapdor-Kleingrothaus H.V., Hellmig J., Hirsch M.* // J. Phys. G. 1998. V.24. P.483.
35. *Klapdor-Kleingrothaus H.V.* // Proc. of the Intern. Symposium on Advances in Nuclear Physics / Eds.: D.Poenaru, S.Stoica. Singapore, 2000. P.123–129.
36. *Klapdor-Kleingrothaus H.V.* // Proc. of Intern. Symposium on Lepton and Baryon Number Violation, Trento, Italy, April 20–25, 1998 / Ed. H.V.Klapdor-Kleingrothaus, I.V.Krivosheina. Bristol, 1999. P.251–301; Preprint hep-ex/9901021.
37. *Klapdor-Kleingrothaus H.V.* // Springer Tracts in Modern Physics. 2000. V.163. P.69–104. Heidelberg, 2000.
38. *Ellis J., Ferstl A., Olive K.A.* // Phys. Lett. B. 2000. V.481. P.304–314; Preprint hep-ph/0001005; Preprint hep-ph/0007113.
39. *Klapdor-Kleingrothaus H.V.* // Proc. of Intern. Workshop on Low Energy Solar Neutrinos (LowNu2), Dec. 4–5, 2000; Proc. of the 2nd Workshop on «Neutrino Oscillations and Their Origin» (NOON'2000), Tokyo, Japan, Dec. 6–8, 2000 / Ed. Y.Suzuki et al. Singapore, 2001.
40. *Klapdor-Kleingrothaus H.V. et al.* MPI-H-V32-2000.
41. *Baudis L. et al.* hep-ex/0012022.
42. *Staudt A., Kuo T.T.S., Klapdor-Kleingrothaus H.V.* // Phys. Lett. B. 1990. V.242. P.17–23.
43. *Tomoda T.* // Rept. Prog. Phys. 1991. V.54. P.53–126.
44. *Haxton W.C., Stephenson G.J.* // Prog. Part. Nucl. Phys. 1984. V.12. P.409–479.
45. *Wu X.R. et al.* // Phys. Lett. B. 1991. V.272. P.169–172.
46. *Wu X.R. et al.* // Phys. Lett. B. 1992. V.276. P.274–278.
47. *Ejiri H. et al.* // Phys. Rev. Lett. 2000. V.85. P.2917–2920; Preprint nucl-ex/9911008.
48. *Danilov M. et al.* // Phys. Lett. B. 2000. V.480. P.12–18.

49. *Gratta G.* // Proc. of Intern. Workshop on Low Energy Solar Neutrinos (LowNu2), Tokyo, Japan, Dec. 4–5, 2000 / Ed. Y.Suzuki. Singapore, 2001. Home page: http://www-sk.icrr.u-tokyo.ac.jp/neutlowe/2/ transparency/index.html.

50. *Fiorini E. et al.* // Phys. Rep. 1998. V.307. P.309.

51. *Fiorini E.* Priv. Communication. Jan. 2001.

52. *Alessandrello A. et al.* // Phys. Lett. B. 1994. V.335. P.519–525.

53. *Alessandrello A. et al.* // Phys. Lett. B. 2000. V.486. P.13–21;
Pirro S. et al. // Nucl. Instr. Meth. A. 2000. V.444. P.71–76.

54. *Giuliani A.* (CUORE Collaboration) // Proc. of «Lepton and Baryon Number Violation in Particle Physics, Astrophysics and Cosmology», Trento, Italy, April 20–25, 1998 / Eds. H.V.Klapdor-Kleingrothaus, I.V.Krivosheina. Bristol, 1999. P.302–308.

55. *Tretyak V.I., Zdesenko Yu.G.* // At. Data Nucl. Data Tables. 1995. V.61. P.43–62.

56. NEMO Collaboration // Contributed Paper for XIX Intern. Conf. of Neutrino Physics and Astrophysics (NEUTRINO'2000), Sudbury, Canada, June 16–21, 2000. LAL 00-31. 2000. P.1–10; NEMO-III Collaboration // Proc. of Intern. Conf. of NANPino2000, Dubna, Russia, July 2000 / Ed. V.Bednyakov et al. 2001.

57. *Fiorini E.* // Proc. of Intern. Conf. of Neutrino Physics and Astrophysics (NEUTRINO'2000), Sudbury, Canada, June 2000 / Ed. A.B.MacDonald et al. 2001.

58. *Gonzalez D. et al.* (IGEX Collaboration) // Proc. of TAUP 99, Paris, France, 1999; Nucl. Phys. Proc. Suppl. 2000. V.87. P.278–280.

59. *Kirpichnikov I.V.* Priv. Communication. June 2000.

60. *Aalseth C.E. et al.* (IGEX Collaboration) // Proc. of 5th Intern. Workshop on Topics in Astroparticle and Underground Physics (TAUP 97), Gran Sasso, Italy, Sept. 7–11, 1997; Nucl. Phys. Proc. Suppl. 1999. V.70. P.236–238.

61. *Aalseth C.E.* (IGEX Collaboration) // Phys. Rev. C. 1999. V.59. P.2108–2113.

62. *Aalseth C.E. et al.* (IGEX Collaboration) // Proc. of 5th Intern. Workshop on Topics in Astroparticle and Underground Physics (TAUP 95), Toledo, Spain, Sept. 17–21, 1995; Nucl. Phys. Proc. Suppl. 1996. V.48. P.223–225.

63. *Brodzinski R.L. et al.* (IGEX Collaboration) // Proc. of 15th Intern. Conf. on Neutrino Physics and Astrophysics (NEUTRINO'92), Granada, Spain, June 7–12, 1992; Nucl. Phys. Proc. Suppl. 1993. V.31. P.76–79.

64. *DeBraekeleer L.* Talk given at the Workshop on the Next Generation U.S. Underground Science Facility, WIPP, Carlsbad, New Mexico, USA, June 12–14, 2000. Home page: http://www.wipp.carlsbad.nm.us/leptontown/workshoptalks/ debraekeleer1/index.htm.

65. Proc. of Intern. Workshop on Low Energy Solar Neutrinos (LowNu2), Tokyo, Japan, Dec. 4–5. 2000 / Ed. Y.Suzuki. Singapore, 2001. Home page: http://www-sk.icrr.u-tokyo.ac.jp/neutlowe/2/transparency/index.html.

66. *Suzuki Y.* for the Collaboration. Preprint hep-ph/0008296.

67. *Fujiwara M. et al.* // Phys. Rev. Lett. 2000. V.85. P.4442–4445; Preprint nucl-ex/0006006; *Bhattacharya M. et al.* // Phys. Rev. Lett. 2000. V.85. P.4446–4449; Preprint nucl-ex/0006005.

68. See: http://www.sns.ias.edu.jnb/.

69. *Edsjo J.* Neutralinos as Dark Matter — Can We See Them? Seminar given in the theory group, Department of Physics, Stockholm University, October 12, 1999. Home page: http://www.physto.se/edsjo/.

70. *Bernabei R. et al.* // Nucl. Phys. B. 1998. V.70. (Proc. Suppl.) P.79.

71. *Bernabei R. et al.* // Nucl. Lett. B. 1998. V.424. P.195; Phys. Lett. B. 1999. V.450. P.448; Phys. Lett. B. 2000. V.480. P.23.

72. *Abusaidi R. et al.* (CDMS Collaboration) // Nucl. Instr. Meth. A. 2000. V.444. P.345; Phys. Rev. Lett. 2000. V.84. P.5699–5703.

73. *Bellini G. et al.* // Phys. Lett. B. 2000. V.493. P.216–228.