Hot and Cold Dark Matter Search with GENIUS *

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Abstract. GENIUS is a proposal for a large volume detector to search for rare events. An array of 40–400 'naked' HPGe detectors will be operated in a tank filled with ultra-pure liquid nitrogen. After a description of performed technical studies of detector operation in liquid nitrogen and of Monte Carlo simulations of expected background components, the potential of GENIUS for detecting WIMP dark matter, the neutrinoless double beta decay in $^{76}$Ge and low-energy solar neutrinos is discussed.

1 Introduction

GENIUS (GErmanium in liquid NItrogen Underground Setup) is a proposal for operating a large amount of 'naked' Ge detectors in liquid nitrogen to search for rare events such as WIMP-nucleus scattering, neutrinoless double beta decay and solar neutrino interactions, with a much increased sensitivity relative to existing experiments [1,2,3]. By removing (almost) all materials from the immediate vicinity of the Ge-crystals, their absolute background can be considerably decreased with respect to conventionally operated detectors. The liquid nitrogen acts both as a cooling medium and as a shield against external radioactivity. The proposed scale of the experiment is a nitrogen tank of about 12 m diameter and 12 m height with 100 kg of natural Ge and 1 ton of enriched $^{76}$Ge in the dark matter and double beta decay versions, respectively, suspended in its center.

To cover large parts of the MSSM parameter space, relevant for the detection of neutralinos as dark matter candidates [4,5], a maximum background level of $10^{-2}$ counts/(kg y keV) in the energy region below 100 keV has to be achieved. In the double beta decay region (Q-value = 2038.56 keV) a background of 0.3 events/(t y keV) is needed in order to test the effective Majorana neutrino mass down to 0.01 eV. This implies a very large background reduction in comparison to our recent best results [6,7] with the Heidelberg–Moscow experiment.

2 Experimental studies and background considerations

To demonstrate the feasibility of operating Ge detectors in liquid nitrogen we performed three experiments in the Heidelberg low level laboratory [8,9]. The goal was to look for possible interferences between two or more naked Ge crystals,

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to test different cable lengths between FETs and crystals and to design and test preliminary holder systems. For crystal masses between 300–400 g we achieved energy resolutions of about 1.0 keV at 300 keV and thresholds of about 2 keV. No microphonic events due to nitrogen boiling beyond 2 keV could be detected. Also, we couldn’t observe any cross talk using only p–type detectors (same polarity for the HV-bias), since cross talk signals have the wrong polarity and are filtered by the amplifier. Concluding, the performance of the Ge detectors is as good (or even better) as for conventionally operated crystals, even with 6 m cable lengths between crystal and FET.

For an estimation of the expected overall background in both low and high energy regions, we performed detailed Monte Carlo simulations of all the relevant background sources. The sources of background can be divided into external and internal ones. External background is generated by events originating from outside the liquid shield, such as photons and neutrons from the Gran Sasso rock, muon interactions and muon induced activities. Internal background arises from residual impurities in the liquid nitrogen, in the steel vessel, in the crystal holder system, in the Ge crystals themselves and from activation of both liquid nitrogen and Ge crystals at the Earth’s surface. For the simulation of muon showers, the external photon flux and the radioactive decay chains we used the GEANT3.21 package extended for nuclear decays.

The simulated geometry consisted of a cylindrical nitrogen vessel of 12 m in diameter and 12 m in height, surrounded by a 2 m thick polyethylene-foam isolation, which is held by two 2 mm thick steel layers. The crystals were held by a holder system of high molecular polyethylene and positioned in the tank centre.

**External background** We simulated the measured photon, neutron and muon fluxes in the Gran Sasso underground laboratory. The underlying assumptions were a 12 m × 12 m nitrogen shield, a 2 m thick boron loaded polyethylene foam isolation and a muon veto with a 96% efficiency on top of the tank. The resulting count rates for both low and high energy regions are shown in Table 1.

The anticoincidence of the 40 (400) Ge-detectors further reduces the effect of muon showers by a factor of 5 (100). Besides muon showers, we considered muon induced nuclear disintegration and interactions due to secondary neutrons generated in the above reactions. Secondary neutron induced interactions in the liquid nitrogen, as well as negative muon capture and inelastic muon scattering reactions generate only a negligible contribution to the overall expected background rate (for details see [2, 3]). In germanium, two n-capture reactions are important (Table 3): $^{70}$Ge(n,γ)$^{71}$Ge and $^{76}$Ge(n,γ)$^{77}$Ge. $^{71}$Ge decays by EC (100%) with $T_{1/2} = 11.43$ d and $Q_{EC} = 229.4$ keV [10]. $^{77}$Ge decays by $\beta^-$-decay with $T_{1/2} = 11.3$ h and $Q_{\beta^-} = 2.7$ MeV [10]. Because of their long half-lives, these decays can not be discriminated by anticoincidence with the muon veto.
Table 1. Resulting count rates for the simulation of the gamma, neutron and muon fluxes measured in the Gran Sasso laboratory, in the energy regions between 11 keV–100 keV and 2000 keV–2080 keV.

| Component          | Count rate (11-100 keV) [events/(kg y keV)] | Count rate (2000-2080 keV) [events/(t y keV)] |
|--------------------|--------------------------------------------|-----------------------------------------------|
| gammas             | $4 \times 10^{-3}$                          | $2 \times 10^{-1}$                            |
| neutrons           | $4 \times 10^{-4}$                          | $6 \times 10^{-3}$                            |
| muon showers       | $2 \times 10^{-3}$                          | $2 \times 10^{-2}$                            |
| $\mu \rightarrow n$, $^{71}$Ge, $^{77}$Ge | $1 \times 10^{-3}$                          | $1.2 \times 10^{-2}$                          |
| $\mu \rightarrow$ caption | $<<1 \times 10^{-4}$                      | $<<1 \times 10^{-4}$                          |

Internal background The assumed intrinsic impurity levels for the simulated materials are listed in Table 2.

Table 2. Assumed intrinsic impurity levels for the simulated detector components.

| Source           | Radionuclide | Purity         |
|------------------|--------------|----------------|
| Nitrogen         | $^{238}$U    | $3.5 \times 10^{-16}$ g/g |
|                  | $^{232}$Th   | $4.4 \times 10^{-16}$ g/g |
|                  | $^{40}$K     | $1 \times 10^{-15}$ g/g |
|                  | $^{222}$Rn   | $3$µBq/m³      |
| Ge crystals      | $^{238}$U    | $<1.8 \times 10^{-15}$ g/g |
|                  | $^{232}$Th   | $<5.7 \times 10^{-15}$ g/g |
| Holder system    | U/Th         | $1 \times 10^{-12}$ g/g |
| Steel vessel     | U/Th         | $5 \times 10^{-9}$ g/g |

The values assumed for the $^{238}$U and $^{232}$Th decay chains in liquid nitrogen have already been reached by BOREXINO for their liquid scintillator. Due to the very high cleaning efficiency of fractional distillation, it is conservative to assume that these requirements will also be fulfilled for liquid nitrogen. The $^{222}$Rn contamination of freshly produced liquid nitrogen was recently measured to be $325$ µBq/m³. Here, an additional underground storage time of 1 month was assumed. This level could be maintained if the evaporated nitrogen is always replaced by Rn-pure nitrogen, previously stored below ground. Surface emanations are reduced to a negligible level for cooled surfaces in direct contact with the liquid nitrogen. The intrinsic impurity levels in Ge crystals are conservative.
upper limits from measurements with the detectors of the Heidelberg–Moscow experiment. We see a clear \(\alpha\)-peak in two of the enriched detectors at 5.305 MeV, and an indication for the same peak in two other detectors. It originates from the decay of \(^{210}\)Po (which decays with 99\% through an \(\alpha\)-decay to \(^{206}\)Pb) and is a sign for a \(^{210}\)Pb contamination of the detectors. The assumed values for polyethylene were reached by the SNO experiment \([19]\), for an acrylic material. The impurity level in steel has been measured by BOREXINO \([20]\).

The results of the simulation of the intrinsic background component \(s\) is given in Table 3. Not included is the contribution from the Ge-crystals (about \(1 \times 10^{-2}\) events/(kg y keV) below 100 keV) since it is very unlikely that the contaminations are intrinsic of the crystals. Most probably they are on the crystal surfaces at the inner contacts. Besides that, it is very unlikely that \(^{210}\)Pb is in equilibrium with \(^{238}\)U, as we assumed. However, for GENIUS, special attention will have to be paid in order to avoid such surface contaminations of the 'naked' crystals.

Table 3. Low and high energy count rates from the intrinsic impurities of the simulated detector components.

| Source | Component | Count rate (11-100 keV) \([\text{events/(kg y keV)}]\) | Count rate (2000-2080 keV) \([\text{events/(t y keV)}]\) |
|--------|-----------|-----------------------------------------------|-----------------------------------------------|
| Nitrogen | \(^{238}\)U intrinsic | \(7 \times 10^{-4}\) | \(2 \times 10^{-4}\) |
| Steel vessel | U/Th | \(1.5 \times 10^{-5}\) | \(3 \times 10^{-3}\) |
| Holder | U/Th | \(8 \times 10^{-4}\) | \(1 \times 10^{-4}\) |

We have estimated the cosmogenic production rates of radioisotopes in the Ge–crystals with the \(\Sigma\) programme \([21]\). Assuming a production and transportation time of 10 days at sea level for the Ge–detectors, and a deactivation time of three years, we obtain the radioisotope concentrations listed in Table 3 (for \(^{68}\)Ge the saturation activity was assumed). All other produced radionuclides have much smaller activities due to their shorter half lives.

The count rate below 11 keV is dominated by X–rays from the decays of \(^{68}\)Ge, \(^{49}\)V and \(^{55}\)Fe (see Table 3). Due to their strong contribution, the energy threshold of GENIUS would be 11 keV, which is still acceptable (as can be seen from Fig. 3).

Between 11 keV and 70 keV the contribution from \(^{63}\)Ni dominates due to the low Q–value (66.95 keV) of the \(\beta^{-}\)-decay. Figure 1 shows the sum and the single contributions from the different isotopes. \(^{68}\)Ge plays a special role. Since it can not be extracted by zone melting like all other, non–germanium isotopes,
Table 4. Cosmogenically produced isotopes in the Ge crystals for an exposure at sea level of 10 days and a subsequent deep underground storage of 3 years (for $^{68}$Ge the saturation activity was assumed).

| Isotope | Decay, $T_{1/2}$ | Energy deposition in the crystal [keV] | $A \, [\mu\text{Bq kg}^{-1}]$ |
|---------|----------------|--------------------------------------|-------------------------|
| $^{49}$V | EC, 330 d  | $E_K$(Ti) = 5, no $\gamma$            | 0.17                    |
| $^{54}$Mn | EC, 312.2 d | $E_\gamma$ = 840.8                  | 0.20                    |
| $^{55}$Fe | EC, 2.73 a  | $E_K$(Mn) = 6.5, no $\gamma$        | 0.31                    |
| $^{57}$Co | EC, 271.3 d | $E_\gamma$ = 136.5                  | 0.18                    |
| $^{60}$Co | $\beta^-$, 5.27 a | $E_{\beta^-}$ = 318, $E_\gamma$ = 1173.2,1332.5 | 0.18 |
| $^{63}$Ni | $\beta^-$, 100.1 a | $E_{\beta^-}$ = 66.95, no $\gamma$ | 0.01                   |
| $^{65}$Zn | EC, 244.3 d | $E_\gamma$ = 1125.2                 | 1.14                    |
| $^{68}$Ge | EC, 288 d  | $E_K$(Ga) = 10.37, $^{68}$Ga decay  | 101                     |

the starting activity would be in equilibrium with the production rate. With a half–life of 288 d it would by far dominate the other background components. A solution could be to process the germanium ore directly below ground or to use high purity germanium which has already been stored for several years in an underground laboratory.

Fig. 1. Background originating from cosmic activation of the Ge crystals at sea level with 10 days exposure and 3 years deactivation.
The sum of all contributions from the cosmogenic activation of the Ge crystals amounts to $5.2 \times 10^{-2}$ counts/(kg y keV) between 11–100 keV, and to $3.6 \times 10^{-2}$ counts/(t y keV) between 2000–2080 keV (a de-enrichment factor of 500 for the $^{70}$Ge in the enriched $^{76}$Ge material was assumed). Since this will be the dominant background component in the low energy region, special attention to short crystal exposure times at sea level is essential.

The relevant cosmogenic isotopes produced in the nitrogen during its transportation at sea level are given in Table 5 along with their decay modes and energies. Their estimated activities for a realistic 10 days exposure to a sea level neutron flux of $8.2 \times 10^{-3}$ cm$^{-2}$s$^{-1}$ (for neutron energies between 80 MeV and 300 MeV) and to a muon flux of $1.6 \times 10^7$ m$^{-2}$d$^{-1}$ along with the induced background rates in the low energy region are also shown.

Table 5. Cosmogenically produced radionuclides in liquid nitrogen at sea level, estimated activities for a 10 d exposure and induced background rates.

| Isotope | $T_{1/2}$, Decay | Energy | Activity [Bq/g] | Rate (11-100 keV) [ev./(kg y keV)] |
|---------|-----------------|--------|-----------------|-------------------------------------|
| $^3$H   | 12.35 y, $\beta^-$ (100%) | $E_{\beta^-} = 18.6$ keV | $3.8 \times 10^{-8}$ | — |
| $^7$Be  | 53.29 d, EC, $\gamma$ (10%) | $E_{\gamma} = 477.61$ keV | $3.7 \times 10^{-9}$ | $8 \times 10^{-3}$ |
| $^{10}$Be | $1.6 \times 10^6$ y, $\beta^-$ (100%) | $E_{\beta^-} = 555$ keV | $8.4 \times 10^{-15}$ | negligible |
| $^{14}$C | $5.7 \times 10^4$ y, $\beta^-$ (100%) | $E_{\beta^-} = 156$ keV | $1.4 \times 10^{-4}$ | $1 \times 10^{-4}$ |

No events of tritium decay were detected in the Ge-crystals, mainly due to the absorption in the dead layer of the p-type Ge detectors. For $^7$Be, the additional assumption of one year of deactivation in Gran Sasso was made. Moreover, it can be expected, that a large fraction of $^7$Be is removed from the liquid nitrogen at the cleaning process for Rn. For the production of $^{10}$Be and $^{14}$C both neutron and muon capture induced channels were considered.

Summing up the background contributions discussed so far, the mean count rate in the low energy region amounts to about $6 \times 10^{-2}$ events/(kg y keV) and to $2.8 \times 10^{-1}$ events/(t y keV) in the region relevant for the $0\nu\beta\beta$-decay.

In Fig. 2 the spectra of individual contributions and the summed up total background spectrum are shown (after three years of storage of the Ge detectors below ground). The low energy spectrum is dominated by events originating from the cosmogenic activation of the Ge crystals at the Earth's surface. Another two years of storage below ground, or production of the detectors in an underground facility would significantly reduce this contribution. For the high-energy region, the results of the simulations are comparable to the aim of 0.3 counts/(t y keV). The background spectrum is dominated by the contribution of external gammas.
(which again reveals the importance of a 12 m LiN shield) followed by the contribution of the cosmogenic $^{60}$Co.

![Graph showing simulated spectra of dominant background sources](image)

**Fig. 2.** Simulated spectra of the dominant background sources for a nitrogen tank of 12 m diameter. Three years of storage below ground for the Ge detectors were assumed. Shown are the contributions from the detector holder system, from the intrinsic nitrogen contamination, from the external natural radioactivity and from the cosmogenic activation of the Ge detectors. The solid line represents the sum spectrum of all the simulated components.

3 Potential of GENIUS to search for rare events

**WIMP dark matter** With 100 kg of natural Ge and a background of $1 \times 10^{-2}$ events/(kg y keV) in the energy region between 11–100 keV, GENIUS could test
a large part of the predicted MSSM parameter space for neutralinos as dark matter candidates. Figure 3 shows a comparison of existing constraints and future sensitivities of cold dark matter experiments, together with the theoretical expectations for neutralino scattering rates [23]. Even if the background would be higher than expected, GENIUS could easily cover the range of positive evidence for dark matter claimed by the DAMA experiment [24]. It would be an independent test by using a different technology and only raw data, without any background subtraction. Moreover, GENIUS would be the only experiment which could test DAMA directly, having a realistic chance to see the predicted seasonal variation of the event rate in 100 kg of detector material.

![Fig. 3. WIMP-nucleon cross section limits as a function of the WIMP mass for spin-independent interactions. The hatched region is excluded by the Heidelberg-Moscow [6] and the DAMA experiment [25]; the plain black curve is the new limit of the CDMS experiment [26]. The dashed lines are expectations for recently started or future experiments, like HDMS [27], CRESST [28], CDMS (Soudan) [29] and GENIUS [3]. The filled contour represents the 2σ evidence region of the DAMA experiment [24]. The experimental limits are compared to expectations (scatter plot) for WIMP-neutralinos calculated in the MSSM parameter space at the weak scale (without any GUT constraints) under the assumption that all superpartner masses are lower than 300 GeV - 400 GeV [23].]

**Neutrinoless double beta decay** Neutrinoless double beta decay provides a powerful method for gaining informations about the absolute neutrino mass scale and a unique method of discerning between a Majorana and a Dirac neutrino. The current most stringent experimental limit on the effective Majorana neu-
trino mass, $\langle m \rangle < 0.36$ eV, comes from the Heidelberg-Moscow experiment \cite{7,9}. For a significant step beyond this limit, much higher source strengths and lower background levels are needed. This goal could be accomplished by the GENIUS experiment operating 300–400 detectors made of enriched $^{76}$Ge (1 ton). With a background rate of 0.3 events/(t y keV) in the energy region between 2000–2080 keV, GENIUS would reach the sensitivity of $\langle m \rangle < 0.01$ eV after one year of measuring time. This would have striking influence on presently discussed neutrino mass scenarios \cite{30} and would allow a breakthrough into the multi TeV range for many beyond standard models \cite{1}. Already now the result from the Heidelberg-Moscow experiment excludes simultaneous solutions for hot dark matter, the atmospheric neutrino problem and the small mixing angle MSW solution of the solar neutrino problem \cite{31}, as well as one of the two solutions for four-neutrino scenarios \cite{32}. GENIUS would determine the mixing in partially or completely degenerate neutrino mass schemes with extreme accuracy, providing informations being complementary to precision tests of cosmological parameters by MAP and Planck \cite{30}. Besides that, it could test the LSND indication for neutrino oscillations. For a detailed discussion of these topics we refer to \cite{3,30}. Moreover, GENIUS would yield information on supersymmetry (R-parity breaking, sneutrino mass), leptoquarks (leptoquark-Higgs coupling or leptoquark mass), compositeness, right-handed W boson mass, test of special relativity and equivalence principle in the neutrino sector, neutrino magnetic moment and others, competitive to corresponding results from future high-energy colliders \cite{3,33,34}.

**Solar neutrinos** The very low background aimed at by GENIUS in the low energy region, its energy threshold of about 11 keV and a target mass of at least 1 ton of natural (or enriched) Ge would open the possibility to look for pp- and $^7$Be solar neutrino interactions in real-time. The detection reaction would be the elastic scattering process $\nu + e^- \rightarrow \nu + e^-$. The maximum electron recoil energy is 261 keV for the pp-neutrinos and 665 keV for the $^7$Be-neutrinos \cite{35}. The dominant part of the signal in GENIUS would be produced by pp-neutrinos (66%) and the $^7$Be-neutrinos (33%) \cite{36}.

A target mass of 1 ton (10 tons) of natural or enriched Ge corresponds to about $3 \times 10^{29}$ ($3 \times 10^{30}$) electrons. Using the cross section for elastic neutrino-electron scattering from \cite{35} and the neutrino fluxes from \cite{37}, the expected number of events in the standard solar model (BP98 \cite{38}) can be estimated:

$$R_{pp} = 68.9 \text{ SNU} = 1.8 \text{ events/day (18 events/day for 10 tons)}$$
$$R_{^7Be} = 28.5 \text{ SNU} = 0.6 \text{ events/day (6 events/day for 10 tons)}$$

The event rates for full $\nu_e \rightarrow \nu_\mu$ conversion are 0.48 events/day for pp-neutrinos and 0.14 events/day for $^7$Be-neutrinos for 1 ton of Ge and ten times higher for 10 tons.

In order for GENIUS to be sensitive to the low-energy solar neutrino flux, the background requirements would be more stringent than for the dark matter
version. A nitrogen shield of 13 m in diameter and 13 m in height is required. Regarding the radiopurity of liquid nitrogen, the values reached at present by the BOREXINO collaboration for their liquid scintillator would be sufficient. More attention has to be paid to the cosmogenic activation of the Ge crystals at the Earth surface. In case of one day exposure, five years of deactivation below ground are required. The optimal solution would be to produce the detectors in an underground facility.

If the signal to background ratio (S/B) in GENIUS will be greater than 1, than the pp- and 7Be-neutrino flux can be measured by spectroscopic techniques alone. If S/B < 1, one can make use of a solar signature in order to derive the flux. The eccentricity of the Earths orbit induces a seasonal variation of about 7% from maximum to minimum. Even if the number of background events is not known, the background event rate and the signal event rate can be extracted independently by fitting the event rate to the seasonal variation. The only assumption is that the background is stable in time and that enough statistics is available. In case of a day/night - variation of the solar neutrino flux, GENIUS would be sensitive to the LOW MSW solution of the solar neutrino problem.

4 Summary and Outlook

The capability of the GENIUS project to search for rare events such as WIMP-nucleus scattering, neutrinoless double beta decay and low energy solar neutrino interactions has been reviewed. After presenting experimental studies which confirm the good performance of ‘naked’ Ge-crystals in liquid nitrogen, the background requirements were discussed in some detail. The results achieved by Monte Carlo simulations for both low and high energy regions are promising.

Reaching the background level aimed at, the GENIUS project could bring a large progress in the field of direct dark matter detection. It could probe a relevant part of the SUSY-WIMP parameter space interesting for the detection of neutralinos, thus possibly deciding whether or not neutralinos are the major component of the dark matter in our Galaxy. In its double beta decay version, GENIUS could deliver important insights on the absolute neutrino mass scale, probing the effective Majorana neutrino mass down to 0.01 eV. Last but not least, it could be the first detector to detect the solar pp neutrinos in real-time.

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