THE GENIUS PROJECT - BACKGROUND AND TECHNICAL STUDIES

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The potential of GENIUS as a dark matter detector is discussed. A study was performed to demonstrate the good behaviour of the proposed detector design of naked HPGe-crystals in liquid nitrogen. The expected background components were simulated and are discussed in some detail. With the obtained background GENIUS could cover a large part of the favoured MSSM parameter-space.

1 Introduction

In modern physics one of the biggest remaining challenges is the question of the nature of dark matter. Enormous efforts are being made to solve this puzzle. One of the most promising theoretical candidates is the neutralino as the lightest supersymmetric particle (LSP) (see, e.g. [1]). Neutralinos can be directly detected through elastic scattering off nuclei in a low background detector.

The present experimental situation concerning direct detection of the LSP is depicted in Fig. 3 (see [3]). The area above the solid lines represents the excluded parts of the \( M_{\text{WIMP}}-\sigma_0 \) parameter space from running experiments (DAMA, Heidelberg-Moscow, CDMS) [4, 5, 6]. Also shown in the figure are the expected sensitivities of experiments presently under construction (CDMS, CRESST, HDMS) [6, 7, 8]. The scatter plot represents allowed solutions for the \( M_{\text{WIMP}}-\sigma_0 \) parameter space from MSSM calculations [1]. Obviously the sensitivities of the running and forthcoming experiments are by far too low to cover a great part of the favoured MSSM parameter space. In order to reach this goal an improvement of the present best sensitivities by three to four orders of magnitudes is required. A promising approach to this problem is the recent Heidelberg GENIUS proposal [9, 10, 11, 12], which suggests application of 100 kg of 'naked' natural germanium detectors for cold dark matter search or 1 ton of enriched \(^{76}\text{Ge}\) for hot dark matter search in liquid nitrogen in an underground setup. In this way all materials are removed from the close vicinity of the detector. Operating HPGe-crystals directly in liquid nitrogen has been discussed earlier [13]. It already has been

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shown that the detectors work well under these circumstances.\(^1\)\(^2\)

The use of liquid nitrogen (another system has been discussed recently\(^3\)) has the following advantages:

- If the tank containing the liquid nitrogen is made big enough, the LN\(_2\) could serve as a shielding against external radioactivity.
- The cooling efficiency would be optimal, since the crystals would be in direct contact with the cooling medium.
- LN\(_2\) can be produced with a high purity.

The LN\(_2\) would basically be the only material surrounding the crystals thus avoiding many dangerous background sources. Under these circumstances the required background index of 0.01 counts/(kg keV y) could be reached for the region relevant for dark matter search below 100 keV. In a first phase it is planned to operate 40 natural germanium-crystals with \(\sim\)2.5 kg each, resulting in an effective mass of \(\sim\)100 kg detector material.\(^4\)\(^5\)\(^6\) A suitable place for the experiment is the Gran Sasso Underground Laboratory.

### 2 Technical possibilities

To prove beyond the first work\(^1\)\(^2\) the technical feasibility of operating ’naked’ HPGe crystals directly in LN\(_2\), two studies were performed. In Fig.1 the three crystals of the second study are shown. The cable length between crystal and FET (the first preamplifier element) were 2m, 4m and 6m. Each crystal had a mass of \(\sim\)300g.
Table 1. Performance of the detectors

| Det #       | cable-length | FWHM at 81keV [keV] | FWHM at 356keV [keV] | threshold [keV] |
|-------------|--------------|---------------------|----------------------|----------------|
| 1. Study    | /            | 1.21±0.01           | 1.51±0.01            | ?              |
| 99031       | 4 m          | 0.98±0.01           | 1.12±0.02            | ?              |
| 99032       | 2 m          | 0.82±0.05           | 1.01±0.02            | 1.85±0.20      |
| 99033       | 6 m          | 0.68±0.05           | 1.04±0.02            | 1.85±0.20      |
| HDMS inner det. | /          | 1.0±0.05            | 1.15±0.1             | 2.5            |

2.1 Microphonics and interferences between detectors

During extensive checks on the oscilloscope no signs of microphonics could be detected. Also in an enforced test, when operating the detectors directly after cooling them to their working temperature, despite the strongly boiling LN$_2$ no signs, neither on the oscilloscope, nor in the recorded spectrum, could be seen. Even when shaking the dewar the detectors did not show an alteration of their performance. Furthermore there was no deterioration in the recorded background spectra taken at the Gran Sasso underground laboratory with respect to the calibration measurements, which would be expected for microphonics in the low energy region.

Moreover no signs of crosstalk between the detectors could be observed in the recorded spectra.

2.2 Electronic noise due to extreme cable lengths

The obtained resolution for the detectors are listed in Table 1. Comparing the results for the ‘naked’ detectors with the performance of the conventionally operated 200g inner HPGe-detector of the HDMS experiment (see Tab. 1) an improvement of the resolution has been obtained even for a cable length of 6m between crystal and FET. The threshold could be lowered to ~2keV. The fact that the best energy resolution was reached for the detector with the longest cable length was due to a change in the capacitance of the preamplifier which was only performed for this detector, whereas for the other two the default setting was left unchanged.

3 Expected background index

To obtain an estimate of the awaited background, Monte Carlo simulations with the code GEANT3.2[17] have been performed.
3.1 External background sources

The gamma flux in the Gran Sasso Underground Laboratory was simulated leading to the conclusion that a tank of 12m in diameter is needed to shield the detectors sufficiently from external gamma-radioactivity. The neutron flux measured in the Gran Sasso has to be taken into account. This flux is initially reduced by the polyethylene foam by 92%. The through going neutrons will be mostly thermalized and captured by the nitrogen through the reactions $^{14}\text{N}(n,p)^{14}\text{C}^*$ and $^{14}\text{N}(n,\gamma)^{15}\text{N}^*$. The main contribution to the background from this component results from the deexcitation of the nuclei. Considering the fact that the thermalization takes part within the first 100 cm of the LN$_2$ shielding, the resulting gammas in the simulation where randomly distributed in the first meter of the shielding. With an additional boron-dotation of the polyethylene ($\sim$1000 kg) a count rate of $\sim 10^{-3}$ counts/(kg keV y) is expected.

The measured muon flux at the Gran Sasso Underground Laboratory is 1.1 m$^{-2}$h$^{-1}$ with a mean energy of $E_\mu = 200$GeV. The effect of muon-showers has been simulated. By the use of a veto shield on top of the tank, reaching an effectivity of 96 % this would yield $\sim 3 \times 10^{-3}$ counts/(kg keV y). This will be further reduced through the anticoincidence between the 40 detectors in the setup.

The number of neutrons induced by muon showers is estimated to $A_n \sim 3.2 \times 10^{-4}$ per m$^2$ resulting in $\sim 2.5 \times 10^3 n/y$ in the whole tank. The only produced long lived isotopes due to neutron-reactions are $^{14}\text{C} (T_{1/2}=5730y)$ and $^{13}\text{N} (T_{1/2}=9.96m)$. The decay of the $^{14}\text{C}$ is negligible due to the long half life and the low decay energy. The cross section for the production of $^{13}\text{N}$ is by two orders of magnitudes lower than the total cross section in the relevant energy region, thus the contribution of these isotopes is negligible.

Other ways of producing long lived isotopes are $\mu$-capture by the $^{14}\text{N}$ nuclei ($\mu+(Z,A)\rightarrow(Z-1,A)^*+\nu_\mu \rightarrow (Z-x,A-y)+n,p,\alpha,\gamma,...$) and inelastic muon scattering ($\mu+N \rightarrow \mu^*+X^*$). The amount of produced isotopes is less then $10^4$ y$^{-1}$ in the tank and is therefore negligible in comparison to the dominant background sources.

3.2 Internal sources

Taking the purity level reached by the Borexino collaboration for steel ($5\times10^{-9}$g/g $^{238}\text{U}$ and $^{232}\text{Th}$), a contribution of $\sim 10^{-4}$ counts/(kg keV y) is expected from the vessel.

The contribution of the LN$_2$ to the background mainly originates from
the nuclear decay chains U/Th, primordial $^{40}$K and $^{222}$Rn from the surroundings. With the limits so far reached by the Borexino-collaboration for purified water, the decay chains and $^{40}$K would contribute with $\sim 4 \times 10^{-3}$ counts/(kg keV y) to the background between 0 keV and 100 keV. For the $^{222}$Rn contamination it is assumed that a purity of 100$\mu$Bq/m$^3$ LN$_2$ can be reached through an efficient isolation ensuring minimal diffusion of $^{222}$Rn into the tank leading to $\sim 5 \times 10^{-3}$ counts/(kg keV y) in the interesting region. Detailed measurements of the purity of LN$_2$ are underway now, first results encourage the assumptions made.

The simulated holder system consisted of two 0.5 cm thick high-molecular polyethylene plates being held by 5 rods of the same material attached to the ceiling of the tank. Motivated by recent results of the SNO collaboration, we assumed a radioactive contamination of the polyethylene 100 times larger than the purity reached by the Borexino collaboration for their liquid scintillator material. With this we obtain $\sim 8 \times 10^{-4}$ counts/(kg keV y) in the relevant energy region.

To estimate the activation of the detector material through cosmic radiation during production and transportation, the $\Sigma$ code was used. The decays of the produced isotopes were simulated. In order to keep the contamination low enough, it will be necessary to produce and transport the crystals within 10 days if no additional shielding is provided. The expected activities of these isotopes yield $\sim 10^{-2}$ counts/(kg keV y).

4 GENIUS as a cold dark matter experiment

The expected overall background is shown in Fig.2. It is evident that it should in principle be possible to reach a background index as low as a few $10^{-2}$ counts/(kg keV y) between 10 keV and 100 keV. With this the GENIUS experiment could cover a major part of the favoured MSSM $M_{WIMP} - \sigma_0$ parameter space (see also Fig.3).

5 GENIUS as a hot dark matter experiment

The expected background for the region of the Q-value of the $0\nu\beta\beta$-decay is $\sim 5 \times 10^{-5}$ counts/(kg keV y). Using 1 ton of enriched $^{76}$Ge detectors would enable GENIUS to test the effective Majorana neutrino mass down to $\sim 0.007$ eV (68 % C.L.) after ten years of measurement. Not only would this allow to make a statement of the contribution of neutrinos to dark matter, also conclusions on neutrino oscillations could be drawn, since the $0\nu\beta\beta$ decay observable $<m_\nu>$ can be expressed in terms of oscillation parameters, if an
Figure 2. Resulting spectra of simulated components. Shown is also the contribution of the $2\nu\beta\beta$-decay, which can be well subtracted from the obtained spectrum. Due to the electron capture reaction of some cosmogenic nuclei and the following emitted Kα, the threshold of the detector will be $\sim 11$ keV.

For the case of degeneracy a 10 ton version of GENIUS with enriched $^{76}$Ge could even cover the small angle MSW solution (see Fig.3).

6 Conclusion

As a preparational step of the GENIUS project, a technical study has been made testing the performance of the new detector design of naked HPGe-crystals operated directly in liquid nitrogen. The attained properties are comparable or even better than the ones of conventionally used HPGe-detectors. In particular we could not discover any signs of microphonics or interference. The investigation of the awaited background components lead to the result that a background index of a few $10^{-2}$ counts/(kg keV y) can be reached in the energy region below 100 keV relevant for the detection of WIMPs. This will allow GENIUS to cover a major part of the favoured MSSM parameter space (see Fig.3) within 3 years of measurement with 100 kg of natural HPGe.
Figure 3. Left: $M_{\text{WIMP}} - \sigma_0$ Limits and favoured region from MSSM calculations (see text). Shown is also the evidence contour for a WIMP signal from the DAMA experiment. Solid lines correspond to exclusion areas from running experiments, dashed lines to future projects. Excluded is the area above the lines. Right: $\Delta m^2 - \sin^2 2\theta$ exclusion plot. Excluded are the areas right of the curves. Shown is also the potential of the GENIUS-experiment as a hot dark-matter detector. In case of degeneracy a 10 ton version of GENIUS could cover both, the small and large angle solution of the solar neutrino problem (from\textsuperscript{27}).

detectors. Using a 1 ton version with $^{76}\text{Ge}$ the effective Majorana neutrino mass could be probed down to 0.01 eV within 1 year, thus making GENIUS a powerfull tool in dark matter search and in the search for other physics beyond the standard model.

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