

# GENIUS: the first real-time detector for solar pp-neutrinos?

Laura Baudis <sup>1</sup>,  
H. V. Klapdor-Kleingrothaus <sup>2</sup>

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

**Abstract.** The GENIUS project is a proposal for a large supersensitive Germanium detector system for WIMP and double beta decay searches with a much increased sensitivity relative to existing and other future experiments. In this paper, the possibility to detect low energy solar neutrinos with GENIUS in real-time through elastic neutrino-electron scattering is studied.

## 1. Introduction

The study of neutrinos coming from the Sun is a very active area of research. Results from five solar neutrino experiments are now available. These experiments measure the solar neutrino flux with different energy thresholds and using very different detection techniques. All of them, the Chlorine experiment at Homestake [1], the radiochemical Gallium experiments, GALLEX [2] and SAGE [3], the water Cerenkov detectors Kamiokande [4] and Super-Kamiokande [5], measure a deficit of the neutrino flux compared to the predictions of the standard solar models (SSM) [6, 7]. Recently it has been stated that it is impossible to construct a solar model which would reconcile all the data [8]. Moreover, a global analysis of the data of all the experiments does not leave any room for the  $^7\text{Be}$  neutrinos [9]. On the other hand the predictions of the SSM have been confirmed by helioseismology [10] to a high precision. An explanation of the results of solar

<sup>1</sup> E-mail: Laura.Baudis@mpi-hd.mpg.de

<sup>2</sup> E-mail: klapdor@daniel.mpi-hd.mpg.

neutrino experiments seems to require new physics beyond the standard model of electroweak interaction.

If neutrinos have non-zero masses and if they mix in analogy to the quark sector, then conversions between different neutrino flavours become possible. Flavour conversions can occur in different physical scenarios, depending on certain parameters on neutrino masses and mixing angles. One oscillation scenario makes use of the MSW-mechanism [11], where the solar  $\nu_e$  transform into other neutrino flavours or into sterile neutrinos as they pass through a thin resonance region near the solar core. The other scenario assumes that the neutrinos oscillate in the vacuum between the Sun and the Earth [12], which means that the oscillation length ‘just so’ matches the Earth-Sun distance.

## 2. The GENIUS Project

GENIUS (GERmanium in liquid NITrogen Underground Setup) is a proposal for operating a large amount of ‘naked’ Ge detectors in liquid nitrogen for dark matter and alternatively  $\beta\beta$ -decay researches [13, 14, 15, 16, 17, 18], with an improved sensitivity of three orders of magnitude relative to present experiments.

The proposed scale of the experiment is a nitrogen tank of about 12 m diameter and 12 m height which contains 100 kg (40 detectors) of natural Ge detectors in its dark matter version, and 1000 kg of enriched  $^{76}\text{Ge}$  detectors in a second step, for neutrinoless double beta decay searches. The liquid nitrogen acts both as a cooling medium for the Ge detectors and as a shielding against external radioactivity. The optimal locations of the experiment would be the Gran Sasso or the WIPP underground laboratories.

In several technical studies it was shown, that Ge detectors work reliably when immersed directly in liquid nitrogen [15, 17, 18]. The obtained performances for the energy threshold and energy resolution were as good as for conventionally operated detectors (i.e. vacuum-tight Cu-cryostat system [19]).

To cover large parts of the MSSM parameter space, relevant for the detection of neutralinos as the dark matter candidate [20, 21], a maximum background level of  $10^{-2}$  counts/(kg y keV) in the energy region between 0–100 keV has to be achieved. This means a very large further background reduction in comparison to our recent best result (20.82 counts/(kg y keV)) [22] with an enriched detector of the Heidelberg–Moscow experiment [23] and to all other running dark matter experiments.

### 3. The solar neutrino spectrum

The Sun acquires its energy by nuclear reactions taking place in the core, mainly via the so-called pp-chain (see Figure 1).

**Figure 1.** Nuclear reactions in the pp-chain in the Sun.

The neutrino spectrum predicted by the SSM for the pp-chain is shown in Figure 2. The dominant part of the flux is emitted at energies below 1 MeV.

The pp neutrinos, emitted in the reaction  $p+p \rightarrow D+e^++\nu_e$ , have a continuous energy spectrum with the endpoint at 420 keV. Their flux is most accurately predicted in the SSM, since it is strongly restricted by the solar luminosity and by helioseismological measurements. The other main features of the solar neutrino spectrum are a strong monoenergetic line at 861 keV, from the reaction  ${}^7\text{Be}+e^-\rightarrow {}^7\text{Li}+\gamma+\nu_e$ , the  ${}^7\text{Be}$  neutrinos, and a continuous spectrum of neutrinos extending up to 15 MeV, due to the reaction  ${}^8\text{B}\rightarrow 2\alpha+e^++\nu_e$ , the  ${}^8\text{B}$  neutrinos. Table 1 gives the solar neutrino fluxes in the SSM with their respective uncertainties (from [25]).

### 4. Present status of the solar neutrino experiments

The solar neutrino problem has been known for more than two decades, since the Homestake experiment reported its first result. At that time, however, it was not clear if the difference between the chlorine measurement and the standard solar model prediction was due to experimental systematics or the uncertainties in the SSM or if it was a sign of new physics. Meanwhile, the observed discrepancy was confirmed by other four

**Figure 2.** Predicted solar neutrino spectrum in the SSM, from [24].

solar neutrino experiments (see Figure 3, from [26]). Model independent analysis performed by many authors (see [8] and references therein) suggest that the solar neutrino problem can only be solved if some additional assumptions are made in the standard electroweak theory. The most generic assumption is to give neutrinos a mass, which leads to neutrino oscillations in vacuum or matter.

Oscillations between two neutrino species are characterized by two parameters:  $\Delta m^2$ , the difference of the squared mass eigenstates, and  $\theta$ , the mixing angle between the mass eigenstates.

The Ga experiments, sensitive to the low-energy pp and  ${}^7\text{Be}$  neutrinos, combined with the Homestake and Super-Kamiokande experiments, which are sensitive to the high-energy  ${}^8\text{B}$  neutrinos, strongly restrict the allowed range of  $\Delta m^2$  and  $\theta$  for all oscillation scenarios. There exist four parameter areas compatible with the results of all existing solar neutrino experiments: the large mixing angle solution (LMA), the small mixing angle solution (SMA), the low mass solution (LOW) and the vacuum oscillation solution

Source	Flux ( $10^{10} \text{ cm}^{-2}\text{s}^{-1}$ )
pp	$5.94 \pm 0.01$
pep	$1.39 \times 10^{-2} \pm 0.01$
$^7\text{Be}$	$4.80 \times 10^{-1} \pm 0.09$
$^8\text{B}$	$5.15 \times 10^{-4} \pm 0.19$

**Table 1.** Solar Standard Model predictions of the neutrino fluxes, from [25]

with strong mixing (see Figure 4 for the MSW-solutions). Up to date, there is no clear evidence for one of the above solutions. To clarify the situation, there is great demand for additional solar neutrino experiments, especially at energies below 1 MeV.

Borexino [27] is now being built up especially to measure the flux of  $^7\text{Be}$  neutrinos in real-time. It will use 300 tons of organic scintillator (100 tons of fiducial volume) to detect recoil electrons from elastic neutrino-electron scattering. Since the scintillator has no directional information and the signal is characterized only by the scintillation light produced by the recoil electron, very stringent constraints on the radiopurity of the scintillator and on the activity of all detector materials are imposed.

So far, there exist three proposals to measure the pp-flux in real-time, HERON [28], HELLAZ [29] and LENS [30].

The HERON project will use  $^4\text{He}$  in its superfluid state (at 20 mK) as the target medium. The detection reaction is elastic neutrino-electron scattering, the electron recoil energy is converted into low-energy elementary excitations of the helium, rotons, which can be detected. For a fiducial volume of seven tons, the total SSM predicted event rate is 14 per day (8 events per day from the pp neutrinos). HERON would measure only the energy distribution of recoiling electrons, without a direct determination of the neutrino energy.

In the HELLAZ project a large TPC ( $2000 \text{ m}^3$ ) filled with gaseous helium at high pressure (5 atm.) and low temperature (77 K) will serve as a target. It is planned to measure both the kinetic energy and the scattering angle of recoil electrons from elastic neutrino-electron scattering and thus to determine the solar neutrino energy. The kinetic energy of recoil electrons is measured by counting the individual electrons in a ionisation cloud generated by the energy loss of the recoil electron due to ionisation in the helium gas. The expected event rate for  $2 \times 10^{30}$  target electrons is 7 per day and 4 per day for pp neutrinos and  $^7\text{Be}$  neutrinos, respectively.

LENSE would be a complementary approach to the above detectors using flavour independent elastic scattering from electrons. The method of neutrino detection is neutrino capture in  $^{82}\text{Se}$ ,  $^{160}\text{Gd}$  or  $^{176}\text{Yb}$ . The

**Figure 3.** Comparison of the total rates predicted in the SSM and the observed rates in the present solar neutrino experiments, from [31].

neutrino captures occur to excited states of the final nuclides, providing a strong signature against radioactive background. The thresholds for neutrino capture are 173 keV for  $^{82}\text{Se}$ , 244 keV for  $^{160}\text{Gd}$  and 301 keV for  $^{176}\text{Yb}$ . Three different techniques for implementation as a solar neutrino detector are explored at present [32]: liquid scintillator loaded with Yb or Gd, scintillating crystals of silicates of Gd (GSO) and time projection chambers with a gaseous compound of isotopic  $^{82}\text{Se}$ .

All of these projects are still in a stage of research and development, they have not yet shown full feasibility for implementation as a solar neutrino detector.

## 5. Time signatures of solar neutrinos

Due to the eccentricity of the Earth orbit, seasonal variations in the flux of solar neutrinos are expected. The number of neutrinos of all flavours

**Figure 4.** The allowed regions (99% C.L.) in  $\Delta m^2 - \sin^2 2\theta$  parameter space for the MSW solution, from [33].

reaching the Earth is larger when the Earth is closer to the Sun than when it is farther away and should vary with  $1/R^2$ , where  $R$  is the Earth-Sun distance,  $R=R_0(1-\epsilon\cos(2\pi t/\text{year}))$ .  $R_0=1\text{AU}$  and  $\epsilon=0.017$ . The neutrino flux thus shows a seasonal variation of about 7% from maximum to minimum. This variation can in principle be used by a real-time solar neutrino experiment to extract the neutrino signal independently of background (if the background is stable in time) and is limited only by statistics.

Beyond the so-called ‘normal’ seasonal variation, an anomalous seasonal variation is predicted for the  $^7\text{Be}$  neutrino flux in case of the vacuum oscillation solution, since their oscillation length in this case is comparable to the seasonal variation of the Earth-Sun distance due to the eccentricity of the Earth orbit. The flux variations in this case are much larger than for the normal seasonal variation, they could serve as a unique signature of vacuum oscillations [12].

If neutrinos oscillate via the MSW-effect, then a regeneration of electron-neutrinos while passing through the Earth is predicted [34]. The so-called 'day/night'-effect is neutrino-energy dependent, its detection would be a strong evidence for the MSW-effect. In Figure 5 (from [35]) the  $\nu_e$  survival probabilities for the MSW solutions computed for the day-time and night-time are shown. At low energies only the LOW solution shows significant differences between the day- and night-time survival probability. Therefore this solution could be tested by a real-time detector of low energy solar neutrinos, in particular by measuring the pp and  ${}^7\text{Be}$  neutrino flux.

**Figure 5.** Survival probabilities for an electron neutrino created in the Sun for the three MSW solutions, from [35]. SMA, LMA, LOW stand for the small mixing angle, the large mixing angle and the low  $\Delta m^2$  MSW-solutions.



## 6. GENIUS as a solar neutrino detector

The goal of the GENIUS project as a dark matter detector is to achieve the background level of  $10^{-2}$  events/kg y keV in the energy region below 100 keV. Such a low background in combination with a target mass of at least 1 ton of natural (or enriched) Ge opens the possibility to measure the solar pp- and  ${}^7\text{Be}$ -neutrino flux in real-time with a very low energy threshold.

### 6.1. Signal Detection

The detection reaction is 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  ${}^7\text{Be}$ -neutrinos [34]. The energy of the recoiling electrons is detected through ionisation in high purity Ge detectors. GENIUS in its 1 ton version would consist of an array of about 400 HPGe detectors, 2.5 kg each. Thus, the sensitive volume would be naturally divided into 400 cells which helps in background discrimination, since a neutrino interaction is taking place in a single cell.

### 6.2. Signal Rates

The dominant part of the signal in GENIUS is produced by pp-neutrinos (66 %) and the  ${}^7\text{Be}$ -neutrinos (33%).

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.

With the cross section for elastic neutrino-electron scattering [34]:

$$\begin{aligned} \sigma_{\nu_e} &= 11.6 \times 10^{-46} \text{cm}^2 & \text{pp} \\ \sigma_{\nu_e} &= 59.3 \times 10^{-46} \text{cm}^2 & {}^7\text{Be} \end{aligned}$$

and the neutrino fluxes [25]:

$$\begin{aligned} \phi_{pp} &= 5.94 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1} \\ \phi_{7\text{Be}} &= 0.48 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1} \end{aligned}$$

the expected number of events calculated in the standard solar model (BP98 [6]) can be estimated:

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

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  ${}^7\text{Be}$ -neutrinos for 1 ton of Ge and ten times higher for 10 tons (see also Table 2)

Case	Ev./day (11-665 keV) (1 ton)	Ev./day (11-665 keV) (10 tons)
SSM	2.4	24
Full $\nu_e \rightarrow \nu_\mu$ conv.	0.62	6.2

**Table 2.** Neutrino signal rates in GENIUS for 1 ton (10 tons) of Germanium.

### 6.3. Background requirements

GENIUS is conceived such that the external background from the natural radioactivity of the environment and from muon interactions is reduced to a minimum, the main background contributions coming from the liquid nitrogen shielding and the Ge detectors themselves. To estimate the expected background counting rate, detailed Monte Carlo simulations and calculations of all the relevant background sources were performed. The sources of background can be divided into external and internal ones. External background is generated by events originating from outside the liquid shielding, 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 Earths surface.

For the simulation of muon showers, the external photon flux and the radioactive decay chains the GEANT3.21 package [36] extended for nuclear decays was used. This version had already successfully been tested in establishing a quantitative background model for the Heidelberg–Moscow experiment [23].

The results of the simulations are given in Table 3 as counting rates per kilogramm detector material, year and keV for each simulated component together with the underlying assumptions for the background sources.

In order for GENIUS to be sensitive to the low-energy solar neutrino flux, a nitrogen shielding of 13 m in diameter is required. Regarding the radiopurity of liquid nitrogen, the values reached at present by the Borexino collaboration for their liquid scintillator would be sufficient. Much 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.

Source	Component	Assumption	Events/ kg y keV 11-260keV
LiN, intrinsic contamination	$^{238}\text{U}, ^{232}\text{T}, ^{40}\text{K}$	3.5, 4.4, $10\times 10^{-16}\text{g/g}$	$3.6\times 10^{-4}$
	$^{222}\text{Rn}$	$0.5\ \mu\text{Bq/m}^3$	$2.5\times 10^{-5}$
Steel vessel	U/Th	$10^{-8}\text{g/g}$	$4.5\times 10^{-5}$
Holder system	U/Th	$10^{-13}\text{g/g}$ ; 13g/det.	$8\times 10^{-5}$
Surrounding	Gammas	GS flux; tank: $13\times 13\text{m}$	$9\times 10^{-4}$
	Neutrons	GS flux	$3\times 10^{-4}$
	Muon showers	GS flux; muon veto 96%	$7.2\times 10^{-6}$
	$\mu \rightarrow \text{n } (^{71}\text{Ge})$	230 capt. in nat. Ge/y	$5\times 10^{-4}$
Cosmogens	$^{54}\text{Mn}, ^{57}\text{Co}, ^{60}\text{Co}$	1d activ., 5y deactiv.	$8\times 10^{-4}$
	$^{63}\text{Ni}, ^{65}\text{Zn}, ^{68}\text{Ge}$		
Total			$3\times 10^{-3}$

**Table 3.** Simulated background sources together with the made assumptions and the resulting event rates in the low energy region of the GENIUS project.

Figure 6 shows the simulated spectrum of the low-energy neutrino signal in GENIUS, together with the total expected background.

If the signal to background ratio  $S/B$  will be greater than 1, than the pp- and  $^7\text{Be}$ -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 Earth's 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 (compare Figure 5).

## 7. Conclusion and Outlook

GENIUS could be the first detector to detect the solar pp neutrinos in real-time. Although this imposes very strong purity restrictions for all the detector components, with a liquid nitrogen shielding of 13 m in diameter and production of the Germanium detectors below ground, it should be

**Figure 6.** Simulated spectra of the low-energy neutrino signal (in the SSM) and the total background in GENIUS (1 ton of natural germanium).

feasible to achieve such a low background level. The advantages are the well understood detection technique (ionization in a HPGe detector), the excellent energy resolution (1 keV at 300 keV), low energy threshold (about 11 keV) and the measurement of the recoiling electrons in real-time.

The good energy resolution for detecting the recoiling electrons would allow for the first time to measure the 1.3 keV predicted shift of the average energy of the beryllium neutrino line. This shift is a direct measure of the central temperature of the Sun [37].

## References

- [1] B.T. Cleveland et al., *Astrophys. J.* 496 (1998) 505
- [2] GALLEX collaboration, W. Hampel et al., *Phys. Lett. B* 447 (1999) 127.
- [3] SAGE collaboration, J.N. Abdurashitov et al., *astro-ph/9907131*
- [4] KAMIOKANDE II collaboration, K.S. Hirata et al., *Phys. Rev. Lett.* 63 (1989) 16.
- [5] The Super-Kamiokande Collaboration, Y. Fukuda et al, *Phys. Rev. Lett.* 81 (1998) 1562.

- [6] J.N. Bahcall, S. Basu and M. Pinsonneault, Phys. Lett. B **433** (1998) 1.
- [7] A. Dar, G. Shaviv, Phys.Rept. **311** (1999) 115.
- [8] H. Minakata, H. Nunokawa, Phys. Rev. D **59** (1999) 073004.
- [9] J.N. Bahcall, Nucl. Phys. A **631** (1998) 29.
- [10] S. Basu *et al.*, Mon. Not. R. Astron. Soc. **292** (1997) 234.
- [11] S.P. Mikheyev, A.Yu. Smirnov, Yad. Fiz. **42** (1985) 1441 and L. Wolfenstein, Phys. Rev. D **17** (1978) 2369
- [12] S.L. Glashow and L.M. Krauss, Phys. Lett. B **190** (1987) 199
- [13] H.V. Klapdor-Kleingrothaus in Proceedings of the First International Conference on Particle Physics Beyond the Standard Model, Castle Ringberg, Germany, 8–14 June 1997, edited by H.V. Klapdor-Kleingrothaus and H. Päs, IOP Bristol, (1998) 485–531 and Int. Journ. Mod. Phys.**A** **13**, (1998) 3953-3992.
- [14] H.V. Klapdor-Kleingrothaus, M. Hirsch, Z. Phys. **A 359** (1997) 351
- [15] H.V. Klapdor-Kleingrothaus, J. Hellmig, M. Hirsch, J. Phys. **G 24** (1998) 483.
- [16] H.V. Klapdor-Kleingrothaus, Y. Ramachers, Europ. J. Phys. **A 3** (1998) 85–92.
- [17] L. Baudis, G. Heusser, B. Majorovits, Y. Ramachers, H. Strecker, H.V. Klapdor-Kleingrothaus, hep-ex/9811040 and Nucl. Instr. Meth. **A 426** (1999) 425
- [18] H. V. Klapdor-Kleingrothaus, L. Baudis, G. Heusser, B. Majorovits, H. Päs, GENIUS, a Supersensitive Germanium Detector System for Rare Events, Report MPI-H-V26-1999, hep-ph/9910205
- [19] G. F. Knoll, Radiation Detection and Measurement, 2. ed., Wiley, 1989
- [20] G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. **267**, (1996) 195.
- [21] V. Bednyakov, H.V. Klapdor-Kleingrothaus, S. Kovalenko, Y. Ramachers, Z. Phys. A **357** (1997) 339.
- [22] L. Baudis *et al.* (Heidelberg–Moscow collaboration), Phys. Rev. D **59** (1998) 022001.
- [23] Heidelberg–Moscow Collaboration, M. Günther *et al.*, Phys. Rev. D **55**, 54 (1997) and L. Baudis *et al.*, Phys. Lett. **B 407** (1997) 219.
- [24] J.N. Bahcall, Phys. Rev. D **44** (1991) 1644.
- [25] J.N. Bahcall, Phys. Lett. B **433** (1998) 1.
- [26] J.N. Bahcall, Astrophys. Journ. **467** (1996) 475.
- [27] Borexino Collaboration, Proposal for a real-time detector for low energy solar neutrinos, Dept. of Physics of the University of Milano (1991).
- [28] R.E. Lanou *et al.*, Phys. Rev. Lett **58** (1987) 2498, S.R. Bandler *et al.*, Phys. Rev. Lett. **74** (1995) 3169 .

- [29] F. Arzarello *et al.*, LPC/94-28 (CERN-LAA/94-19), J. Seguinot *et al.*, LPC/95-08 (CERN-LAA/95-11), J. Seguinot *et al.*, LPC/96-31 (CERN-LAA/96-05).
- [30] R.S. Raghavan, Phys. Rev. Lett. **78** (1997) 3618.
- [31] J.N. Bahcall, [www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html](http://www.sns.ias.edu/~jnb/SNviewgraphs/snviewgraphs.html)
- [32] LENS collaboration, Letter of Intent, LNGS, Italy 1999.
- [33] J.N. Bahcall, P.I. Krastev, A.Yu. Smirnov, Phys. Rev. **D 58** (1998) 096016.
- [34] J.N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press 1989
- [35] J.N. Bahcall and P.I. Krastev, Phys. Rev. C **56** (1997) 2839.
- [36] GEANT3.21 Detector description and simulation tool, Geneva 1993
- [37] J.N. Bahcall, Phys. Rev. Lett. **71** (1993) 2369.