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Detection of low energy solar neutrinos with HPGermanium

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Abstract. The potential of the GENIUS proposal [1] to measure the spectrum of low energy solar neutrinos in real time is studied. The detection reaction is elastic neutrino-electron scattering $\nu + e \rightarrow \nu + e$. The energy resolution for detecting the recoil electrons is about 0.3 %, the energy threshold is a few keV. The expected number of events for a target of one ton of natural germanium is 3.6 events/day for pp-neutrinos and 1.3 events/day for ^{7}Be-neutrinos, calculated in the standard solar model (BP98 [2]). It should be feasible to achieve a background low enough to measure the low energy solar neutrino spectrum.

All solar neutrino experiments measure a deficit of the neutrino flux compared to the predictions of the standard solar model (SSM) [2]. These predictions have recently been confirmed by helioseismology [3] to a high precision, a fact which strongly disfavours astrophysical solutions proposed to explain the discrepancies between the theory and measurements. An explanation of the results of solar neutrino experiments seems to require new physics beyond the standard model of weak interaction. The most robust predictions of the SSM are for the pp, pep and ^{7}Be fluxes, the pp-flux being most strongly constrained by the solar luminosity. In this context, a real time measurement of the pp-flux would be of crucial importance, since any deviation from the predicted flux would be a signature for neutrino flavour oscillations. So far, there exist three proposals to measure the pp-flux in real time, HERON [4], HELLAZ [5] and LENS [6], all of them still in a stage of development. In this letter, we explore the potential of the GENIUS project to measure the pp- and ^{7}Be-neutrino flux by the elastic scattering process $\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$.

GENIUS is a detector proposed to search for dark matter WIMPs and for the neutrinoless double beta decay using ionization in natural and enriched ^{76}Ge HPGe detectors, respectively [1]. In a first step (dark matter version), GENIUS would operate about 40 natural Ge detectors (100 kg) in a 12×12 m tank filled with liquid nitrogen. The nitrogen acts both as cooling medium for the Ge crystals and as shielding against the natural radioactivity of the environment. For almost complete covering of the MSSM parameter space predicted for neutralinos as dark matter candidates, a background counting rate of 0.01 events/kg y keV in the energy region below 100 keV is required. Such a low background opens the possibility to measure the pp and the ^{7}Be neutrino flux in real time with the specific high energy resolution of Ge detectors and an energy threshold of a few keV.

The reaction used to detect solar neutrinos is the elastic neutrino electron scattering: $\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$. The maximum electron recoil energy is 261 keV for the pp-neutrinos and 665 keV for the ^{7}Be-neutrinos [7]. The recoil electrons can be detected through their ionization in a HPGe detector with an energy resolution of 0.3%. The detection rates for the pp and ^{7}Be-fluxes, calculated for the SSM [2], are $\mathrm{R}_{pp} \simeq 70$ SNU and $\mathrm{R}_{^7Be} \simeq 26$ SNU (1 SNU = 10^{-36}/(s target atom)). For one ton of natural Ge (corresponding to 6×10^{29} electrons), the total rates are $\mathrm{R}_{pp} \simeq 3.6$ events/day and $\mathrm{R}_{^7Be} \simeq 1.3$ events/day, assuming the detection of all electrons. This is about ten times higher than the rates in present radiochemical Ga-experiments. The event rates for full $\nu_e \rightarrow \nu_\mu$ conversion are 0.96 events/day for pp-neutrinos and 0.28 events/day for ^{7}Be-neutrinos. GENIUS can measure only the energy distribution of the recoiling electrons, whereas the energy of the incoming neutrinos is not directly determined. However, due to the excellent energy resolution of the detectors and the difference in the elastic scattering cross section of electron and muon neutrinos, a comparison of the energy spectrum of recoiling electrons with the theoretical prediction of the SSM can be made. Due to its relatively high counting rate, GENIUS will be able to test the MSW flavour conversion solution via the day-night modulation of the neutrino flux and the vacuum-oscillation solution via the seasonal flux variation.

The possibility to operate 'naked' Ge-crystals directly in liquid nitrogen has been investigated in three consecutive technical studies [9–11]. It has been shown that the performance of the detectors is as good as for conventionally operated Ge diodes. The energy resolution of a 400 g detector is 1 keV at 300 keV and the energy threshold is 2.5 keV. No microphonic events beyond the threshold, no interference between two or more crystals and no signal deterioration up to cable lengths of 6 m between crys-

Table 1. Background and neutrino induced signal in GENIUS in the energy region from 11 keV to 260 keV

Source	Component	Assumption	Events/(kg y keV)] (11-260 keV)
LiN, intrinsic	^{238}U, ^{232}T, ^{40}K	3.5, 4.4, 10×10^{-16}g/g	3.6×10^{-4}
contamination	^{222}Rn	0.5 μBq/m^3	2.5×10^{-5}
Steel vessel	U/Th	10^{-8}g/g	4.5×10^{-5}
Holder system	U/Th	10^{-13}g/g; 13g material/det.	8×10^{-5}
Surrounding	Gammas	GS flux; tank: 13×13 m	9×10^{-4}
	Neutrons	GS flux	3×10^{-4}
	Muon showers	GS flux; muon veto	7.2×10^{-6}
	$\mu \rightarrow$ n (^{71}Ge)	2.3×10^{2} capt. in nat. Ge/y	5×10^{-4}
Cosmogens	^{54}Mn,^{57}Co,^{60}Co,^{63}Ni, ^{65}Zn,^{68}Ge	1d activ., 5y deactiv.	8×10^{-4}
Total			3×10^{-3}
Signal (pp + ^{7}Be)			5.8×10^{-3}

tals and FET were observed. To estimate the expected background, detailed Monte Carlo simulations were performed [10]. Table 1 shows the results of simulations for the main simulated components together with the assumptions about the material radiopurities and used fluxes. A background counting rate of 10^{-2} events/kg y keV, as achieved in [10], would still be a factor of two higher than the neutrino induced signal, which is 5.8×10^{-3} events/kg y keV in the energy region from 0 to 260 keV. Therefore, a clear neutrino signal above background, assuming no background subtraction (with the exception of the $2\nu\beta\beta$-decay induced signal), requires some additional assumptions in comparison to [10]. First, in order to obtain a high count rate, one ton of natural Ge (~ 300 Ge detectors) has to be used. This represents a very low target mass compared to other solar neutrino detectors. The high counting rate is a consequence of the low energy threshold for single electron recoil detection (11 keV in the worst case), making GENIUS sensitive to a very large part of the pp-neutrino flux (about 10^4 times higher than the ^{8}B-flux). The tank diameter has to be increased to 13 m in order to provide sufficient shielding from the natural radioactivity of the Gran Sasso walls (alternatively an outer water shielding could be used). Regarding muon showers, the count rate is reduced by a factor 100 with respect to [10], due to the anticoincidence of the 300 Ge detectors [9]. For the intrinsic contamination of the liquid nitrogen the simulation was updated with the last measurements for ^{238}U and ^{232}Th of the liquid scintillator of Borexino [12] and with the ^{222}Rn contamination measurements of liquid nitrogen [13] (see Table 1). Regarding the holder system, 130 g of holder material per detector were assumed in [10]. A new technical study revealed the possibility to use only 3 g of material per detector in total [11]. In the actual simulation, 13 g material per detector were assumed. From the produced radionuclides by muon generated neutron interactions in the liquid nitrogen, only the excited ^{14}C* nuclei yield a non-negligible count rate [10]. However these gamma rays can be discriminated by the anticoincidence with a muon veto shield. Not considered in [10] were neutron interactions in the Ge detectors themselves. In 1 ton of natural Germanium, 2.3×10^2 neutrons/y due to muon interactions are produced. For the low energy region the most signifikant reaction is the ^{70}Ge(n,γ)^{71}Ge capture reaction. ^{71}Ge decays through EC (100%) with $T_{1/2} = 11.43$ d and $Q_{EC} = 229.4$ keV [14] and can not be discriminated by the anticoincidence method.

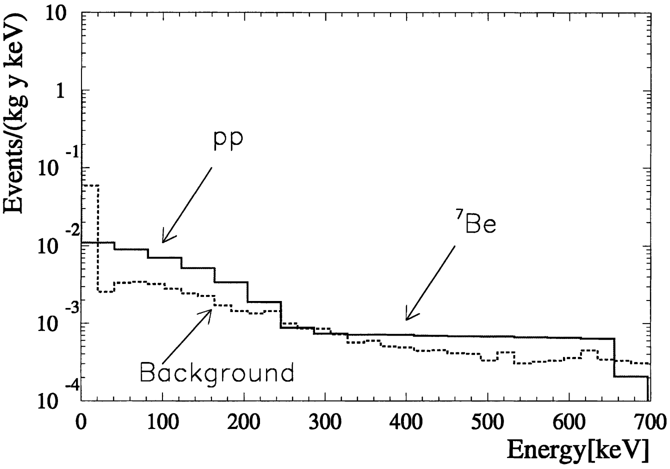

Fig. 1. Simulated spectra of the low energy neutrino signal (in the SSM) and the total background in GENIUS (1 ton of natural germanium)

The cosmic activation of the Ge crystals during their production and transportation at sea level accounts for the still most dangerous background. In [10], 10 days of exposure at sea level and 3 years deactivation in low level environment were assumed. To reduce the cosmogenic background to an acceptable level, a maximum activation time of 1 day and a deactivation time of 5 years is required. This requires production of the detectors in underground facilities and a short transportation time with strong shielding. The double beta decay of ^{76}Ge (7.8% in natural Ge) yields 3×10^{-2} events/kg y keV in the 11-260 keV energy region. This dominates by far the other background sources. However, due to the knowledge of the half-life of the decay [15], the spectral shape and the amount of ^{76}Ge nuclei in the detector, this component can be calculated and subtracted. Figure 1 shows the expected electron recoil spectrum obtained by MC simulations, using the total pp- and ^{7}Be-flux from [2] and the electron spectrum of ν-e scattering from [8], together with the expected background spectrum.

With the above assumptions, the signal to background ratio is about 2:1. Such a ratio would be sufficient for an unambiguously detection of electron recoils from solar pp and ^{7}Be neutrinos. The good energy resolution of the detector and the timing information of the signals would further help to discriminate the signal from background events, due to the expected shape of the recoil electrons (which depends directly on the neutrino energy spectrum) and due to a possible time variation of the neutrino induced signal.

In summary, we investigated the capability of the GENIUS project to detect the solar pp- and ^{7}Be-neutrino flux via electron-neutrino elastic scattering reactions. The detection rate of pp-neutrinos is 3.6 events/day and 1.3 events/day for ^{7}Be neutrinos in the SSM [2]. The required background rate for a 2:1 signal to background ratio is about 3×10^{-3} events/kg y keV in the energy region from 11 to 260 keV. Although this imposes very strong purity restrictions for all the detector components, a liquid nitrogen shielding of 13 m in diameter and production of the Germanium detectors below ground, it should be feasible to achieve such a low background level. The advantages of the experiment 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 pp-flux is most accurately predicted by solar models and strongly constrained by the solar luminosity and helioseismological measurements. A measurement of the pp- and ^{7}Be-neutrino flux by GENIUS could provide an essential contribution to solve the solar neutrino puzzle within a reasonable time scale.

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