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Supernova Registration in Water Cherenkov Veto of Dark Matter Detectors

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Abstract. Registration of supernova neutrinos is one of the main goals of large underground neutrino detectors. We consider the possibility of using the large water veto tanks of future dark matter experiments as the additional facilities for supernova detection. Simulations were performed for registration of Cherenkov light in 2 kt water veto of Darkside-20k from high energy positrons created by supernova electron antineutrinos via inverse beta decay reaction. Comparison between characteristics of different supernova neutrino detectors are presented.

1. Introduction

The next core-collapse supernova in our Galaxy can be detected by several neutrino detectors in different locations on Earth. Some main features of these detectors joined in the SNEWS (SuperNova Early Warning System) are summarized in table 1 [1, 2].

Table 1. SNEWS detectors.

Detector	Type	Location	M, kt	N_{IBD}	E_{th}, MeV
IceCube	[a]L.S. Water	Antarctic	0.6/PMT	N/A	-
Super-K	Water	Japan	32	7000	7.0
LVD	Scint.	Italy	1	300	4.0
KamLAND	Scint.	Japan	1	300	0.35
Borexino	Scint.	Italy	0.3	100	0.2
Daya Bay	Scint.	China	0.33	110	0.7
HALO	Pb	Canada	0.08	30	N/A

[a] Long String

Galactic supernova (SN) explosions are very rare events with the rate of only a few per century [3]. Taking into account the final (90–95 %) duty cycle of neutrino detectors operation it is important to have a collection of different working facilities in the case of next SN in our

Galaxy to measure all neutrino flavours at different Earth locations. Detection of SN neutrino events will allow the precision study of neutrino oscillation physics and astrophysics of supernova burst.

Veto systems of forthcoming underground experiments devoted to the direct searches for dark matter Weakly Interactive Massive Particles (WIMP) [4–8] also can be used for SN detection. To suppress effectively the neutron background of cosmogenic origin these future generation experiments must use the effective veto-shielding based on water Cherenkov and (or) liquid scintillators with the veto target masses in the range of 100 ton up to 2 kilotons. Such big target masses are enough for SN confident registration with the number of detected neutrino events compatible to events from SN 1987A [9]. The costs of such implementation are reasonably small, taking into account the existing infrastructure in dark matter experiments (PMTs and data acquisition electronics of veto system). As the example we consider the use of large 2 kT Water Cherenkov Veto (WCV) of DarkSide-20k dark matter detector as the additional facility for future SN detection and report the results of Monte-Carlo simulation. The Darkside-20k detector is the next step in the DarkSide dark matter search program at the Laboratori Nazionali del Gran Sasso in Italy with the main goal of direct WIMP detection [4, 5].

2. Neutrino Detection in Water Cherenkov Veto (WCV)

The most significant SN neutrino detection reaction in water target is the inverse beta decay (IBD):

$$\tilde{\nu_e} + p \longrightarrow n + e^+; \tag{1}$$

The threshold of the reaction is $E_\nu = 1.8$ MeV. At zero order in $1/M_n$ the total cross section of the IBD reaction is [10, 11]:

$$\sigma(E_\nu) = \frac{2\pi^2/m_e^5}{f^R_{p.s.}\tau_n} E_e^{(0)} p_e^{(0)}, \tag{2}$$

where τ_n is the measured neutron lifetime, $f^R_{p.s.} = 1.7152$ is the phase space factor, including the Coulomb, weak magnetism, recoil and other radiative corrections, $E_e^{(0)} = E_\nu - (M_n - M_p)$ is the positron energy at zero order.

Also all neutrino flavors can be detected via neutrino-electron elastic scattering:

$$\nu + e^- \longrightarrow \nu + e^-; \tag{3}$$

The differential cross section of this reaction is [12]

$$\frac{d\sigma}{dT_e} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 + (g_V^2 - g_A^2)\frac{m_e T_e}{E_\nu^2}\right], \tag{4}$$

where G_F — the Fermi coupling constant, $g_A = \pm 1/2$ and $g_B = 2sin^2\theta_W \pm 1/2$ for ν_e and ν_x, respectively, $g_A \rightarrow -g_A$ for antineutrinos.

3. Supernova Spectrum

A standard supernova at a distance $d = 10$ kpc, with the total energy released in the explosion $E^{tot} \sim 3 \times 10^{53}$ erg and antineutrino average energy $\langle E_\nu \rangle = 12$ MeV has been taken as a sample. Spectrum of neutrinos emitted by a supernova [12]:

$$f(E_\nu) = \frac{128}{3}\frac{E_\nu^3}{\langle E_\nu \rangle^4} exp(-\frac{4E_\nu}{\langle E_\nu \rangle}), \tag{5}$$

The time-integrated flux for single neutrino flavor is

$$\frac{dF}{dE_\nu} = \frac{1}{4\pi d^2}\frac{E_\nu^{tot}}{\langle E_\nu\rangle} f(E_\nu), \tag{6}$$

where E_ν^{tot} is the total energy of single neutrino flavor.

The observed positron spectrum in the detector can be calculated as

$$\frac{dN}{dT_e} = N_T \int_{E_{min}}^{\infty} dE_\nu \frac{dF}{dE_\nu}(E_\nu)\frac{d\sigma}{dT_e}(E_\nu, T_e) \tag{7}$$

and is represented in figure 1. N_T is the number of target protons in the detector.

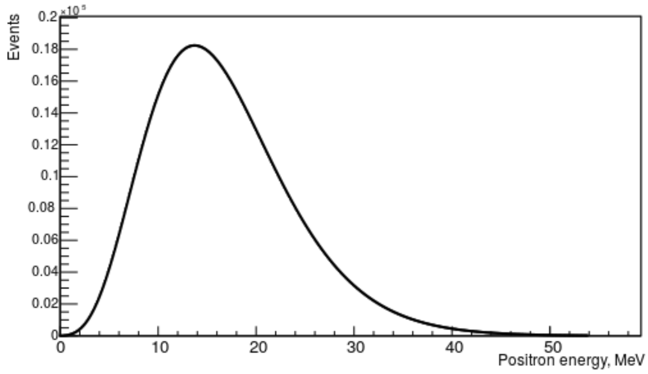

Figure 1. Positron energy spectrum in IBD reaction from the sample supernova

4. Results

Monte-Carlo simulations with Geant4 packet were performed for registration of Cherenkov light in WCV from high energy positrons created by SN electron antineutrinos via IBD reaction. Positrons were generated with energy spectrum from figure 1 isotropically and uniformly all over the water volume.

The results of Monte Carlo simulation for WCV with 80 20" PMTs are presented in figures 2 and 3. In figure 2 one can see the distribution of number of detected photoelectrons in IBD reaction from sample supernova. Two dimensional histogram in figure 3 represents the relation between number of detected photoelectrons and positron energy from IBD reaction after applying the cut on triggering at least 4 PMTs in one event. This condition simulates trigger of a real detector.

For comparison, Super-Kamiokande-II and DarkSide-20k parameters are presented in table 2, where m_w — the weight of water volume, N_{PMT} — numbers of PMTs, η — photocathode coverage, N_{pe} — number of detected photoelectrons per MeV of positron energy, ε — fraction of detected events upon condition of triggering at least 4 PMTs in one event, N_{IBD} — expected number of detected events via IBD reaction for sample supernova, N_{scatt} — via neutrino-electron elastic scattering. SK-II has yield about 6 photoelectrons from Cherenkov light per MeV of electron energy [13](experimental value). In case of DS-20k WCV simulation average number of detected photoelectrons equals to 0.8 per MeV.

Expected number of events in DS-20k in case of standard supernova is 362 for inverse beta decay and 21 for neutrino-electron elastic scattering.

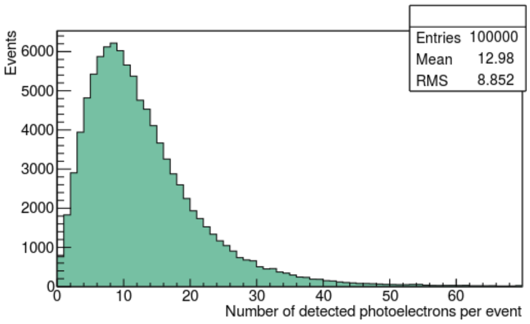

Figure 2. Distribution of number of detected photoelectrons from IBD reaction

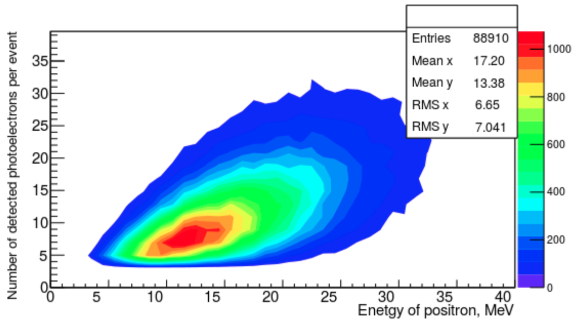

Figure 3. Relation between number of detected photoelectrons and corresponding value of positron energy (cut on 4 PMTs coincidence)

Table 2. Detectors parameters.

m_w, kt	N_{PMT}	$\eta, \%$	N_{pe}, MeV^{-1}	ε	N_{IBD}	N_{scatt}	
Super-K	32	11129	40	6	-	5662	352
DS20k WT	2.2	80	1.5	0.8	88.9%	362	21

5. Conclusions

The expected number of IBD antineutrino events in Cherenkov veto for standard galactic Supernova is similar with the expected rates from other SN detectors operated now. The results obtained from the simulation show the possibility of using the WCV of DarkSide-20k detector as the additional facility for future supernova detection.

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