Sodium Chloride as a Target for Supernovae Neutrinos

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***Abstract*. According to the rotating collapsar model, the gravitational stellar collapse occurs in two stages. During the first stage the electron neutrinos with energies 20-50 MeV are mainly emitted. Previously iron has been considered as a target for detecting neutrinos of such energies. This paper shows that adding NaCl to the structure of iron-scintillation detectors can both significantly improve the neutrino type identification and increase active mass of existing detectors.**

***Keywords*: Supernovae neutrinos, sodium chloride**

I. INTRODUCTION

The standard Supernovae collapse model is developed long ago but it fails to explain the envelope ejection during star explosion and the signal from the SN1987A supernova explosion on February 23, 1987, 2:52 UT in the LSD [1].
Some other gravitational collapse models were developed. The mentioned effect is most naturally explained within the rotating collapsar model developed by V.S. Imshennik [2] which predicts the two-stage neutrino emission. During 1st phase the electron neutrino with average energies 30-40 MeV are emitted [3], during the 2nd one all neutrino types. Iron was considered as a target for detecting the neutrino of such energies [3]- [6]. It was shown [5], [6] that (ν_e, ^{56}Fe) interaction products can be well detected in the large volume scintillation counters, for example, in the LVD apparatus with a 1000 tons active mass of scintillator and equal amount of iron in supporting structure. LVD expects to detect more than 200 events due to interactions of neutrinos with iron nuclei in case of Supernova burst in the Galaxy centre [5]. Neutrino interaction with iron may contribute up to 75%, mainly in the high-energy part of the spectrum, into the total amount of events detected during the 1st collapse stage.

II. THE INTERACTION OF ELECTRON NEUTRINO WITH COMMON SALT

The interactions of electron neutrinos with common salt one can detect via following reactions:

$$\nu_e + Na \to e^- + Mg, \quad (1)$$

$$\nu_e + Cl \to e^- + Ar. \quad (2)$$

It should be taken into account that natural chlorine consists of two isotopes with mass number 35 (75.5%) and 37 (24.5%) while sodium consists of one isotope ^{23}Na. The reaction 1 energy threshold is ∼4 MeV, and the reaction 2 threshold is ∼800 keV for ^{37}Cl, while for ^{35}Cl it is ∼5 MeV. During interaction of e^- with sodium there is a high probability of the birth of magnesium nucleus in the excited state, which de-excites via ∼7.5 MeV gamma-quantum emission. The argon excitement is very weak.

III. THE INR RAS EXPERIMENT "COLLAPSE"

The "Collapse" experiment of INR RAS is located in the salt mine near Arteomovsk (Ukraine) at the depth of 570 m. w. e. It presents a cylindrical tank, 556 cm in diameter and 547 cm in height [7] filled with 105 tons of liquid white-spirit based scintillator (C_nH_{2n},$\overline{n} = 9.6$, [8]).
The MC simulation of the "Collapse" experiment was performed using Geant4 on the following conditions: The unlimited amount of common salt[1] was placed around cylindrical tank of 2.8 m radius and 5.8 m height at the distance of 3 m from its outer surface.
Initially, only electron tracking through the matter was taken into account. The generation point was distributed uniformly around the salt volume, and the velocity direction was isotropic. The information about energy yield was recorded in every event. The detection efficiency ε was determined as a ratio of events with tank energy release greater than 5 MeV to the total amount of events simulated. The values of ε as a function of electron energy and amounts of salt mass that has "taken part" in the simulation are given in Table I. The values of the "effective" mass (the mass of the target assuming ε =1) are also presented.
One can note, that in spite of small values of detection efficiency at large values of salt thickness, the quick increase in mass taking part in the interaction leads to the increase of the effective mass.
In the second variant of calculations the mono-directional neutrino flux was considered and the products of the reaction 1 were simulated. The electron "kept in memory" the direction of coming neutrino (the electron output angle was chosen randomly but not more than 30° with respect to the direction of neutrino coming), gamma-quantum with the energy of 7.5 MeV had an isotropic distributed velocity. The generation point was chosen uniformly in the salt volume.
The detection efficiencies for different salt thicknesses

[1] Really, the thickness of 2 m was regarded.

TABLE I:

E_{e^-}, MeV	<1.5 m			<1 m			<0.5 m			<0.3 m		
	ε	M, t	Mε	ε	M, t	Mε	ε	M, t	Mε	ε	M, t	Mε
40	0.016		13.1	0.024		12.7	0.05		12.8	0.07		10.6
50	0.020		16.4	0.030		15.9	0.06		15.3	0.09		13.6
60	0.025	820	20.5	0.037	529	19.6	0.07	256	17.9	0.11	150	16.6
70	0.029		23.8	0.043		22.8	0.08		20.4	0.12		18.1
80	0.034		27.9	0.051		27.0	0.10		25.6	0.14		21.1

TABLE II:

E_{e^-}, MeV	<1.5 m			<1 m			<0.5 m			<0.3 m		
	>0	>3	>5	>0	>3	>5	>0	>3	>5	>0	>3	>5
30	0.069	0.027	0.022	0.104	0.041	0.033	0.199	0.079	0.064	0.295	0.117	0.097
40	0.078	0.031	0.026	0.117	0.047	0.040	0.222	0.090	0.075	0.329	0.135	0.114
50	0.087	0.037	0.030	0.130	0.055	0.045	0.247	0.105	0.088	0.358	0.154	0.132
80	0.102	0.045	0.038	0.152	0.067	0.058	0.285	0.126	0.109	0.399	0.182	0.160

and detection thresholds (in MeV) obtained are presented in Table II.

IV. LVD Experiment Modification

The description of the LVD apparatus located in Gran Sasso underground laboratory (Italy) and consisting of 840 scintillation counters with a volume of 1.5 m^3 each was given in the literature repeatedly [9]. The detector consists of 3 towers of 7 levels each. Every tower has 5 columns, column includes 8 counters per level.

If we can add the salt plates with dimensions 0.3*6.2*1.03 m into the 0.7 m wide corridors between columns (one plate has mass of 5.2 tons), the total mass of the salt per apparatus would be 437 tons.

The simulation of the neutrino interaction with matter was performed in the same way as in the 2nd variant for "Collapse" experiment, i.e. electron "keeps in memory" the neutrino direction, gamma-quantum if it is emitted has the isotopic velocity distribution. The detection efficiencies obtained are given in Table III.

Since the considered neutrino energies are large enough, the energy yield can exceed the given threshold (5 MeV) in several (mainly, two) LVD counters. Thus we introduce two terms of efficiency: ε_1 presents the number of events with energy release higher than the threshold at least in one counter to the total number of events simulated, while ε_2 stands for number of counters with energy release greater than the threshold. To compare, the values of detection efficiency of neutrino interaction with iron obtained under the same conditions (the presence of salt between columns):

$$\nu_e + Fe \to e^- + Co \qquad (3)$$

are given in two last columns of Table III.

The comparison of data of two last columns of Table III with the results of [5], [6] shows that the presence of salt decreases significantly the reaction 3 detection efficiency but the introduction of salt plates in the LVD structure seems to be reasonable as the gain in the target mass increase exceeds the loss due to absorber mass increase.

Let us assume that specific (per one neutron) interaction cross sections for iron, sodium and chlorine are equal (this may lead to underestimation for sodium). Starting from number of iron, sodium and chlorine nuclei being included in the modified in such a way LVD experiment one can obtain that for 700 interactions[2] due to reaction 3 there would be 113 interactions with sodium and 180 interactions with both chlorine isotopes. One can expect 415 (or 447 if we take into account the simultaneous triggering of several counters) detected events of these 1000 interactions, so the total efficiency would exceed 40%. The introduction of common salt into the LVD structure would increase the expected number of events by about 30% compared to the existing construction.

Bold histogram in Figure 1a shows the energy spectrum of detectable events due to neutrino interactions with salt and iron. The charge current reactions 1 and 2 are suitable for the establishment of maximum energy of coming electron neutrinos using the maximum in the energy spectrum of events.

However, the placing of such a wide (30 cm) salt plate into the LVD corridors may be not practicable. While choosing the salt plates thickness one should note that larger values of thickness increase the interactions number but the specific peak of 7 MeV blurs. It would be more real and reasonable to place vertical salt plates (20 cm thick) in the corridors between columns as well as horizontal plates (10 cm thick) above the scintillation tanks. It may give the principal capability not only to establish the fact of the Supernova burst but to determine the direction of neutrino coming.

The more precise calculations require the exact values of the cross-sections of reactions 1 and 2 for ^{35}Cl.

V. The energy spectra in different collapse models

One can compare the numbers obtained with those that would be detected via inverse beta-decay (IBD) reaction in the standard collapse model framework:

$$\overline{\nu_e} + p \to e^+ + n, \qquad (4)$$

[2]This number of interactions could be associated with the detection of monoenergetic (E∼50 MeV) electron neutrinos emitted from a rotating collapsar located in the centre of the Galaxy [5].

TABLE III:

E_{e^-}, MeV	Electron		Electron & 7.5 MeV gamma-quantum		Reaction 3	
	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2
40	0.163	0.167	0.255	0.274	0.404	0.426
50	0.226	0.234	0.316	0.346	0.483	0.522
60	0.283	0.300	0.364	0.405	0.533	0.590
70	0.337	0.363	0.410	0.466	0.579	0.651
80	0.385	0.421	0.449	0.518	0.599	0.694

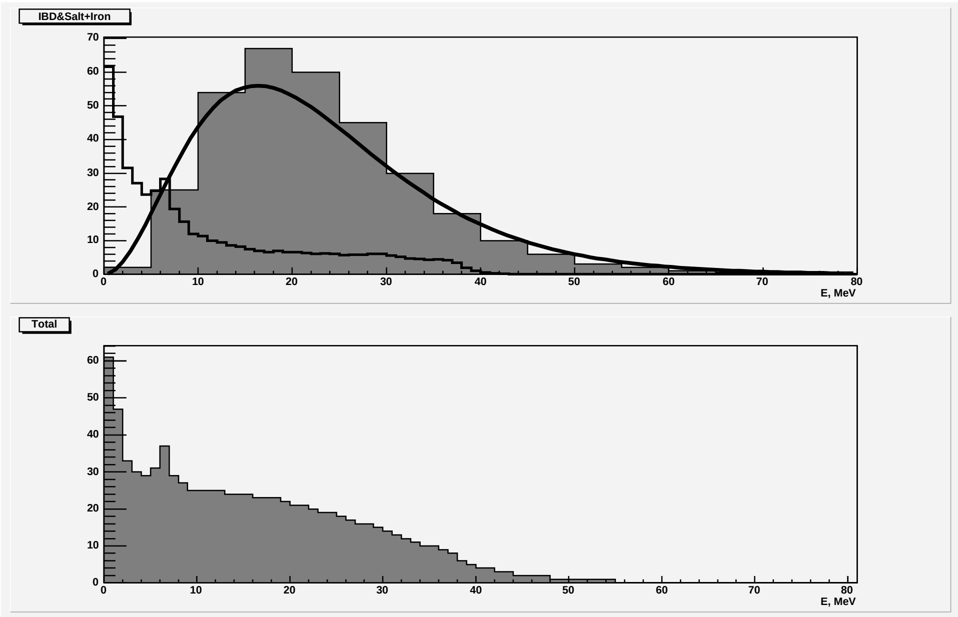

Fig. 1: a) Energy spectrum of events due to IBD reaction 4 at the star neutrinosphere temperature 5 MeV (darkened); fit by the function $AE^2/[exp(E/B)+1]$ is also shown and total energy spectrum of reactions 1-3 for a neutrino energy of $\sim 50MeV$ (bold line); b) The sum of the plots in panel (a) for 320×0.3 events from reaction 4 and 450 events from neutrino interactions with salt and iron; number of events is plotted on the ordinate axis.

with the following neutron capture $n+p \to d+\gamma$. The cross-section is $\sigma \approx 9.3E_{e^+}^2 \times 10^{-44}cm^2$, and $E_{e^+} = E_{\overline{\nu_e}} - 1.3MeV$. So if $E_{\overline{\nu_e}} \sim 20MeV$ one can take $E_{e^+} \approx E_{\overline{\nu_e}}$. The positron gives fast trigger pulse, while the gamma-quantum ($E_\gamma = 2.2MeV$) pulse is detected within the time window of 1 ms.

There are 8.6×10^{28} protons per 1 ton of scintillator with chemical composition C_nH_{2n}, and for the whole apparatus (1000 tons) we obtain 8.6×10^{31} protons. Assuming Supernovae burst parameters to be $R \sim 10kpc = 3.125 \times 10^{22}cm$ and $\varepsilon_\nu^* \sim \frac{1}{6} \times 5 \times 10^{53}erg = 5.17 \times 10^{64}$ eV we can obtain the number of antineutrino interactions with protons:

$$N = \frac{1}{4\pi R^2}\frac{\varepsilon_\nu^*}{E_{nu}}\sigma \times \left(2\frac{M}{\mu}N_A\right) \approx 20.4E[MeV].$$

If the star neutrinosphere temperature is equal to 5 MeV, LVD should detect $\sim$ 320 events due to IBD reaction with the energy spectrum shown in Figure 1a). One should take into account that only $\sim$ 30% of these events would be similar to the events caused by neutrino interactions with salt and iron due to the absence of accompanying small energy pulse in the triggered counter (the same counter detection efficiency of the neutron generated in 4 is about 70%). Adding ”salt” and ”iron” events to the IBD ones leads to the energy spectrum that is shown in Figure 1b).

One should note that even in the case when electron neutrino with energy ∼50 MeV and antineutrino with the average energy ∼15 MeV are emitted simultaneously LVD apparatus is capable to detect neutrino peak (7 MeV) in the total response separating the types of neutrino coming.

Besides, adding common salt to the LVD structure can increase the neutron detection efficiency up to 80% since the chlorine nuclei have large neutron capture cross-section. This will improve not only the antineutrino events detection efficiency but also the neutrino types discrimination using both event spectrum and specific signature of IBD reaction 4.

VI. CONCLUSIONS

The astrophysical parameters of Supernova burst have not been well established yet so the situation may improve only after the next burst observation. So, the existence of the experiments sensible to the different neutrino types is of a great importance. The total number of detectable events due to neutrino interactions with nuclei via neutral and charged currents depends strongly on neutrino energy and, therefore, collapse model.

VII. Acknowledgements

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