ANALYSIS OF THE SN1987A TWO-STAGE EXPLOSION HYPOTHESIS WITH ACCOUNT FOR THE MSW NEUTRINO FLAVOUR CONVERSION

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Detection of 5 events by the Liquid Scintillation Detector (LSD) on February, 23, 1987 was interpreted in the literature as a detection of neutrinos from the first stage of the two-stage supernova collapse. We pose rigid constraints on the properties of the first stage of the collapse, taking into account MSW neutrino flavour conversion and general properties of supernova neutrino emission. The constraints depend on the unknown neutrino mass hierarchy and mixing angle θ_{13}.

SN1987A was the only supernova to date which produced a measured neutrino signal. Four experiments reported the detection of neutrinos: LSD [1,2] (Liquid Scintillator Detector), KII [3] (Kamiokande II), IMB [4] (Irvine-Michigan-Brookheaven) and BST [5] (Baksan Scintillator Telescope). While LSD registered neutrino burst at 2:52UT, February 23, the other three experiments – at 7:35UT February 23 (UT stands for Unitary Time). Each experiment reported only *one* burst: LSD observed no statistically significant counterpart for the KII, IMB and BST neutrino signals and vice versa. This puzzling discrepancy could be, in principle, explained by a two-stage supernova collapse hypothesis, as was stated in a number of works. [6,7,8,9,10] Various two-stage supernova collapse models, proposed in this works, implied the transition from a protoneutron star to a black hole and/or the formation and evolution of a close binary system inside the exploding star. Rigid constraints on the properties of the first stage of two-stage collapse scenarios can be posed, MSW effect [11,12] in the matter of the star being of crucial importance. For example, it was shown [13] that accounting for the neutrino flavour conversion can spoil the reported [10] concordance of the rotating collapsar model with the data. Analysis, independent of the particular collapse model, was also performed. [14] In the present note we report the results of the extended analysis. [15] It provides a more elaborate statistical study of the data and accounts for the supernova shock wave effect, which may influence neutrino flavour conversion. [16]

Table 1: Type, working material and working mass (in tons) of the detectors, numbers of events ($N_{\rm ev}$) at 2:52 and 7:35 (according to the cited references).

	LSD	KII	IMB	Baksan
Type	scintillator	cherenkov	cherenkov	scintillator
Material	C_nH_{2n} 90t Fe 200t	H_2O 2140t	H_2O 5000t	C_nH_{2n} 200t
$N_{\rm ev}$ at 2:52	5 [1,2]	2 [3,7]	0 [4]	1 [5]
$N_{\rm ev}$ at 7:35	2 [10]	11 [3]	8 [4]	6 [5]

Detector characteristics and numbers of registered events at 2:52 and 7:35 are given in Table 1. We discuss only the first stage of the presumable two-stage collapse and, accordingly, only the first neutrino signal, which occurred at 2:52. Moreover, we compare only LSD and KII signals, and do not use IMB and BST data.

It should be noted that the imitation rate from the background for the LSD event cluster at 2:52 was fairly small - 0.7 per year. [1,2] This justifies the attempts to find an explanation for the LSD neutrino signal.

Reactions essentially relevant for neutrino and antineutrino detection in LSD and KII are listed below. Each reaction is relevant for the detector(s) indicated in parentheses.

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad ({\rm KII, LSD}) \tag{1}$$

$$\begin{array}{lllll} \nu_e + {\rm Fe} & \rightarrow & e + {\rm Co}^* & ({\rm LSD}) & \qquad \nu_l + {\rm Fe} \rightarrow \nu_l + {\rm Fe}^* \quad ({\rm LSD}) \\ \nu_e + {\rm O} & \rightarrow & e + {\rm F}^* & ({\rm KII}) & \qquad \bar{\nu}_x + {\rm Fe} \rightarrow \bar{\nu}_x + {\rm Fe}^* \quad ({\rm LSD}) \end{array} \tag{2}$$

Here and in what follows $l = e, \mu, \tau$; $x = \mu, \tau$, and superscript "*" denotes the exited states of the nuclei, which immediately decay to ground ones emitting nucleons and gammas. The role of reactions which involve exited states of nuclei for neutrino detection is discussed in detail elsewhere. [10,17]

In 1987 only reaction (1) was regarded to allow supernova neutrino detection. However, effective electron antineutrino detection area for KII exceeded those for LSD substantially. Numerous studies[3,9,18,19] indicated that LSD signal could hardly be attributed to (7-12) MeV electron antineutrino flux. We focus our attention on the other possibility, which was elaborated[10,17] only in 2004: the idea was that neutrinos (not antineutrinos) of sufficiently high (30-50 MeV) energy produced the signal in LSD through the reactions on iron and carbon nuclei. Effective LSD and KII areas for ν_l and $\bar{\nu}_e$ detection are given in Table 2. Cross sections for reactions (2) are tabulated elsewhere. [20,21]

One could infer from Table 2 that no contradiction between LSD and KII event numbers would occur if supernova neutrino flux was composed of electron and non-electron neutrinos of appropriate energies. However the question is weather such flux content is possible in principle. To answer this question one should consider supernova neutrino emission and flavour conversion.

Neutrinos and antineutrinos of all three flavours can be created during the collapse of the iron core in the centre of the star. All reactions in which they are created conserve lepton flavour. Moreover, muon neutrinos are produced in the same reactions as tau-neutrinos. Therefore in *any* collapse model neutrino fluxes satisfy the following conditions:

$$F^0_x \equiv F^0_{\nu_\mu} = F^0_{\nu_\tau} = F^0_{\bar{\nu}_\tau} = F^0_{\bar{\nu}_\mu}, \qquad 0 \leq F^0_{\nu_e} - F^0_{\bar{\nu}_e} \leq \frac{N_{\rm e}^{\rm Core}}{4\pi L^2} = 0.34 \frac{M_{\rm Core}}{2M_\odot} \cdot 10^{10}{\rm cm}^{-2} \tag{3}$$

Table 2: Effective areas (measured in 10^{-10} cm^2) for ν_l and $\bar{\nu}_e$ detection in KII and LSD.

E_ν(MeV)	ν_e, LSD	ν_e, KII	ν_y, LSD	ν_y, KII	$\bar{\nu}_e$, LSD	$\bar{\nu}_e$, KII
30	2.1	3.2	0.42	0.31	6.9	114
40	5.8	10.4	1.1	0.41	12.2	202
50	12.3	30.8	2.4	0.51	19.0	316
60	22.3	69.7	4.3	0.62	27.4	455

Table 3: p and $\bar{p}$ for different values of θ_{13} and neutrino mass hierarchies; $\sin^2\theta_{12} = 0.28$.

	$\theta_{13} \lesssim 3\cdot 10^{-3}$	$3\cdot 10^{-3} \lesssim \theta_{13} \lesssim 3\cdot 10^{-2}$	$3\cdot 10^{-2} \lesssim \theta_{13} \lesssim 0.17$
Normal hierarchy	$p = \sin^2\theta_{12}$ $\bar{p} = \cos^2\theta_{12}$	$0 \le p \le \sin^2\theta_{12}$ $\bar{p} = \cos^2\theta_{12}$	$p = 0$ $\bar{p} = \cos^2\theta_{12}$
Inverted hierarchy		$p = \sin^2\theta_{12}$ $0 \le \bar{p} \le \cos^2\theta_{12}$	$p = \sin^2\theta_{12}$ $\bar{p} = 0$

Here $F^0_{\nu_l,\bar{\nu}_l}$ is the time- and energy-integrated flux of an (anti-)neutrinos. Upper index "0" denotes that it is an original flux, i.e. such a flux which would reach the earth if there were no flavour conversion in the matter of the star. $M_{\text{Core}} = (1.4 - 2.2)M_\odot$ is the mass of the iron core,[22] $N_{\text{e}}^{\text{Core}}$ is the number of electrons in the core and $L = 52$kpc is the distance between the supernova and the earth.

Fluxes at the earth $F_{\nu_l,\bar{\nu}_l}$ are linear combinations of original fluxes:[23]

$$\begin{array}{rclcrcl} F_{\nu_e} & = & pF^0_{\nu_e} + (1-p)F^0_x & \qquad & F_{\nu_\mu} + F_{\nu_\tau} & = & (1-p)F^0_{\nu_e} + (1+p)F^0_x \\ F_{\bar{\nu}_e} & = & \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_x & \qquad & F_{\bar{\nu}_\mu} + F_{\bar{\nu}_\tau} & = & (1-\bar{p})F^0_{\bar{\nu}_e} + (1+\bar{p})F^0_x \end{array} \tag{4}$$

Coefficients p, $\bar{p}$ (see Table 3 [23]) depend on the unknown neutrino mass hierarchy and neutrino mixing angle θ_{13}.

Upper bounds on original fluxes F^0_x and $F^0_{\nu_e}$ follow immediately from eq.(4) and Table 3:

$$F^0_x \le \frac{1}{1-\bar{p}} F_{\bar{\nu}_e} \le 3.6 F_{\bar{\nu}_e}, \qquad F^0_{\nu_e} \le \frac{1}{\bar{p}} F_{\bar{\nu}_e}. \tag{5}$$

1 Results

We numerically investigated $P(F^0_{\nu_e}, F^0_{\bar{\nu}_e}, F^0_{\nu_x},)$, the probability that fluxes $F^0_{\nu_e}$, $F^0_{\bar{\nu}_e}$ and F^0_x after the flavour conversion according to eq.(4) produced not less than 5 events in LSD and not more than 2 events (with energies less than 12-14 MeV) in KII (the details are given elsewhere [15]). Possible effects due to shock wave propagation were taken into account. The results proved to be stable under the reasonable variation of the input cross sections and detector efficiencies. They lead to the following conclusions concerning the first stage of the two-stage SN1987A explosion models.

(1) In the case of small neutrino 1-3 mixing angle, $\theta_{13} < 0.003$, two-stage SN1987A explosion models are disfavoured by the data, independently of the neutrino mass hierarchy.

(2) Non-electron neutrino and antineutrino production had to be severely suppressed during the first stage of the collapse, independently of the neutrino mass hierarchy and mixing angle θ_{13} :

$$F^0_x \lesssim 10^8 \text{cm}^{-2}. \tag{6}$$

This means that at the first stage of the collapse there was no thermal equilibrium, even rough.

(3) In the case of normal mass hierarchy and large 1-3 mixing angle, $\theta_{13} > 0.03$, in order to

explain the data one should imply emission of very energetic ($E \gtrsim 60$ MeV) electron neutrinos, ν_e, at the first stage of the explosion; at the same time the suppression of $\bar{\nu}_e$ production should be assumed:

$$F^0_{\nu_e} \simeq (0.3 - 0.5) \cdot 10^{10}\text{cm}^{-2}, \qquad F^0_{\bar{\nu}_e} \lesssim 10^8\text{cm}^{-2}. \tag{7}$$

In addition, large values of the collapsing core mass, $M_{\text{Core}} \gtrsim 2M_\odot$, were necessary. A powerful shock wave could further complicate the agreement of the data with the theory.

(4) In the case of inverted mass hierarchy and large 1-3 mixing angle, $\theta_{13} > 0.03$, the data can be explained by the moderate energy (30 MeV$\lesssim E \lesssim$ 45 MeV) electron neutrino and antineutrino emission at the first stage of the explosion with fluxes of order of 10^{10}cm^{-2}. A powerful shock wave could worsen the agreement of the data with the theory.

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