Constraints on neutrino mixing angle $\theta_{13}$ and Supernova neutrino fluxes from the LSD neutrino signal from SN1987A

Oleg Lychkovskiy *a,b

a Institute for Theoretical and Experimental Physics
117218, B.Cheremushkinskaya 25, Moscow, Russia
b Moscow Institute of Physics and Technology
141700, 9, Institutskii per., Dolgoprudny, Moscow Region, Russia

Abstract

Detection of 5 events by the Liquid Scintillation Detector (LSD) on February, 23, 1987 was recently interpreted as a detection of the electron neutrino flux from the first stage of the two-stage Supernova collapse [1][2]. We show that, if neutrino mass hierarchy is normal, such interpretation excludes values of neutrino mixing angle $\theta_{13}$ larger than $3 \cdot 10^{-2}$, independently of the particular Supernova collapse model. Also constraints on the original fluxes of neutrinos and antineutrinos of different flavours are obtained.

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Neutrino signal from the Supernova SN1987A, which explosion was observed on February, 23, 1987, was detected by four experiments. LSD experiment reported the detection of 5 events at the Unitary Time 2:52UT, February 23, 1987 [3],[4], while KII, IMB and Baksan experiments reported the detection of 11, 8 and 5 events, correspondingly, at 7:35UT February 23, 1987 [5],[6],[7]. We shall call 2:52UT the LSD time, and 7:35UT – the IMB time. KII, IMB and Baksan did not see any considerable cluster of events at the LSD time, while LSD did not see such a cluster at the IMB time. A description of the combined time sequence of all detected events may be found in [1]. For a long time it was believed that all four detectors are sensitive almost only to the electron antineutrinos, KII and IMB being several times more sensitive than LSD. Thus absence of a signal in KII and IMB at the LSD time remained an unsolved puzzle. Recently the following solution

*e-mail: lychkovskiy@mail.ru
was proposed [1,2]: LSD included a large amount of Fe and thus was sensitive to the energetic electron neutrinos ($\varepsilon_\nu \sim 40\text{MeV}$) through the reaction

$$\nu_e + \text{Fe} \rightarrow \text{Co}^* + e^-.$$  \hspace{1cm} (1)

It was a unique LSD feature in comparison with three other detectors. According to [1], [2] the LSD neutrino signal is interpreted as the detection of 5 electron neutrinos of energies of about 40MeV. This corresponds to the total electron neutrino flux at the Earth

$$F_{\nu_e} \sim 10^{10}\text{cm}^{-2}.$$  \hspace{1cm} (2)

This flux was too small to produce a considerable cluster of events in KII, IMB and Baksan, as their sensitivity to the electron neutrinos was lower.

Total flux of electron antineutrinos at the Earth at the LSD time had to be much smaller,

$$F_{\bar{\nu}_e} \lesssim 10^9\text{cm}^{-2},$$  \hspace{1cm} (3)

otherwise it would be detected by KII [3] and IMB [6]. The crucial for the subsequent argumentation fact is that

$$F_{\bar{\nu}_e} \lesssim 10^{-1}F_{\nu_e}.$$  \hspace{1cm} (4)

As for the absence of the event cluster in LSD at the IMB time, it is explained by two factors:

1. small LSD electron antineutrino sensitivity (compared to other detector sensitivities), which prevented LSD from the electron antineutrino detection;
2. softness of the spectrum of electron neutrinos at the IMB time, which, due to the high energy threshold of the reaction (1), prevented LSD from the electron neutrino detection.

The existence of two neutrino signals from SN1987A, separated by more than four hours, implies that the Supernova core collapse proceeded in two stages. One of the models of such a collapse, aimed at the explanation of the LSD signal, was proposed by Imshennik and Ryazhskaya in [1]. According to it, at the first stage of the collapse almost exclusively electron neutrinos were produced, electron neutrino luminosity being $L_{\nu_e} \sim 10^{53}\text{erg}$, which is sufficient to produce electron neutrino flux (2). However, Imshennik and Ryazhskaya did not take into account neutrino flavour conversion inside the Supernova progenitor star. Lunardini and Smirnov pointed out (see note added to [8]) that taking such conversion into account breaks the agreement between the collapse model [1] and the LSD data. Namely, if the neutrino mass hierarchy is normal ($m_3 > m_1, m_2$) and neutrino mixing angle $\theta_{13}$ is larger than $\sim 10^{-2}$, then all neutrinos produced as electron ones are converted to the mixture of $\mu$- and $\tau$-neutrinos and thus can not be detected by LSD. If the neutrino mass hierarchy is inverted or $\theta_{13} \ll 10^{-2}$, then the electron neutrino flux at the Earth is suppressed by the factor $\sin^2 \theta_{12} \simeq 0.3$ and thus the original luminosity $L_{\nu_e}$ three times larger than in [1] is required to explain the LSD signal. It should be emphasized, that Lunardini and Smirnov regard their result as an argument against the model by Imshennik and Ryazhskaya [1] rather than a constraint on the mixing angle $\theta_{13}$ and electron neutrino luminosity $L_{\nu_e}$.

In this note we show, that if we admit the interpretation of the LSD neutrino signal proposed in [1,2] and take into account the absence of the neutrino signal in KII and
IMB at the LSD time, we may constrain neutrino mixing angle $\theta_{13}$ in the case of normal neutrino mass hierarchy independently of the particular Supernova collapse model. Also constraints on the original neutrino fluxes (i.e. fluxes, produced in a Supernova core) may be obtained. Constraints on the mixing angle $\theta_{13}$ and original electron neutrino flux coincide with the results of [8].

We make the following assumptions regarding original fluxes:

$$F_0^0 \equiv F_{\nu_{\mu}}^0 = F_{\nu_{\tau}}^0 = F_{\bar{\nu}_{\mu}}^0 = F_{\bar{\nu}_{\tau}}^0 \leq F_{\nu_e}^0, F_{\bar{\nu}_e}^0. \quad (5)$$

This assumptions are natural (see, for example, [9]). They follow from two facts. First, in Supernova $\mu$- and $\tau$-neutrinos are always produced in pairs with their antiparticles. Second, there are more electron (anti-)neutrino production channels than non-electron ones:

$$e^+ + n \to \bar{\nu}_e + p,$$
$$e^- + p \to \nu_e + n,$$
$$A + A' \to A + A' + \nu + \bar{\nu},$$
$$e^+ + e^- \to \nu + \bar{\nu}, \quad (6)$$

where $A, A'$ are nuclei, and $\nu$ stands for a neutrino of arbitrary flavour.

Due to the matter effect neutrino flux of a given flavour is modified in the outer layers of the Supernova progenitor star. As detectors are sensitive almost only to electron neutrinos or antineutrinos, we are interested in the electron neutrino and antineutrino fluxes at the Earth $F_{\nu_e}$ and $F_{\bar{\nu}_e}$. They are connected to the original fluxes as follows [10]:

$$F_{\nu_e} = pF_{\nu_e}^0 + (1 - p)F_x^0,$$
$$F_{\bar{\nu}_e} = \bar{p}F_{\bar{\nu}_e}^0 + (1 - \bar{p})F_x^0, \quad (7)$$

$p$ and $\bar{p}$ being the electron neutrino and antineutrino survival probabilities. Note that from (5) and (7) one may get

$$F_x^0 \leq F_{\nu_e} \leq F_{\nu_e}^0, \quad F_x^0 \leq F_{\bar{\nu}_e} \leq F_{\bar{\nu}_e}^0. \quad (8)$$

Probabilities $p$ and $\bar{p}$ depend on the neutrino mass hierarchy and on the value of the mixing angle $\theta_{13}$. We distinguish three cases: NL (Normal hierarchy, Large angles), IL (Inverted hierarchy, Large angles), AS (Any hierarchy, Small angles). Here large angles stand for $\theta_{13} \gtrsim 3 \cdot 10^{-2}$, while small angles stand for $\theta_{13} \lesssim 3 \cdot 10^{-3}$. Remind that current experimental limit is $\theta_{13} < 0.17 \quad [11]$. Survival probabilities are given by (see [10], [12])

$$p = \sin^2 \theta_{13} \approx 0, \quad \bar{p} = \cos^2 \theta_{12}, \quad NL$$

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We omit obvious factor $R_{ns}^2/R^2$ in all expressions for the fluxes at the Earth $F_{\nu_e}$ and $F_{\bar{\nu}_e}$ (eqs. 7, 8, 10–16). Here $R$ is the distance between the Supernova and the Earth, $R_{ns}$ is the neutrino sphere radius. In the spherically symmetrical case original luminosity of neutrinos and antineutrinos of a given flavour may be obtained from the corresponding original flux through $L = 4\pi R_{ns}^2 \epsilon F$, where $\epsilon$ is a mean (anti-)neutrino energy.
\[ p = \sin^2 \theta_{12}, \quad \bar{p} = \sin^2 \theta_{13} \approx 0, \quad \text{IL} \]

\[ p = \sin^2 \theta_{12}, \quad \bar{p} = \cos^2 \theta_{12}, \quad \text{AS} \]

Let us consider this cases separately.

\textbf{NL}. From (7) and (8) we get

\[ F_{\nu_e} \simeq F_{\nu_e}^0, \quad F_{\bar{\nu}_e} \geq F_{\bar{\nu}_e}^0. \]

Consequently, \( F_{\nu_e} \lesssim F_{\nu_e} \), which is in contradiction with experimental result [14]. Thus this case is excluded.

\textbf{IL}. From (7) we get

\[ F_{\nu_e} = \sin^2 \theta_{12} F_{\nu_e}^0 + \cos^2 \theta_{12} F_{\bar{\nu}_e}^0, \quad F_{\nu_e}^0 \simeq F_{\bar{\nu}_e}, \]

thus, taking (11) into account,

\[ F_{\nu_e}^0 = \frac{1}{\sin^2 \theta_{12}} (F_{\nu_e} - \cos^2 \theta_{12} F_{\nu_e}) \simeq 3 F_{\nu_e}. \]

Here we used \( \sin^2 \theta_{12} \simeq 0.3 \).

\textbf{AS}. From (7) we get

\[ F_{\nu_e} = \sin^2 \theta_{12} F_{\nu_e}^0 + \cos^2 \theta_{12} F_{\bar{\nu}_e}^0 \]

\[ F_{\bar{\nu}_e} = \cos^2 \theta_{12} F_{\nu_e}^0 + \sin^2 \theta_{12} F_{\bar{\nu}_e}^0, \]

and, consequently,

\[ F_{\nu_e}^0 \leq F_{\nu_e} \]

\[ F_{\bar{\nu}_e} \leq F_{\bar{\nu}_e}^0 \leq \frac{1}{\cos^2 \theta_{12}} F_{\bar{\nu}_e} \simeq 1.4 F_{\nu_e} \]

\[ F_{\nu_e}^0 = \frac{1}{\sin^2 \theta_{12}} (F_{\nu_e} - \cos^2 \theta_{12} F_{\bar{\nu}_e}^0) \simeq 3 F_{\nu_e}. \]

Note, that we did not take into account modifications of the fluxes inside the Earth due to the matter effect, in spite of the fact that neutrinos from SN1987A crossed the Earth on their way to each of the detectors. A detailed study of the Earth matter effects was performed in [10],[13]. From this papers it follows that such effects provide a correction to the fluxes of interest not greater than 20% (for neutrino energies about 40 Mev). Thus equalities and inequalities (11)-(12) are valid with 20% precision, which is better than statistical uncertainties of determination of fluxes \( F_{\nu_e} \) and \( F_{\bar{\nu}_e} \). As for eq.(10), it is not influenced by the Earth matter effect at all. Indeed, in the \textbf{NL} case the correction to the electron neutrino flux \( F_{\nu_e} \) is absent, and corrected electron antineutrino flux reads (see [10],[13])

\[ F_{\bar{\nu}_e} = (\cos^2 \theta_{12} - f_{reg}) F_{\bar{\nu}_e}^0 + (\sin^2 \theta_{12} + f_{reg}) F_{\bar{\nu}_e}^0, \]

\[ F_{\bar{\nu}_e}^0 = (\cos^2 \theta_{12} - f_{reg}) F_{\nu_e}^0 + (\sin^2 \theta_{12} + f_{reg}) F_{\nu_e}^0, \]

\[ F_{\nu_e} = \sin^2 \theta_{12} F_{\nu_e}^0 + \cos^2 \theta_{12} F_{\bar{\nu}_e}^0. \]
where $f_{\text{reg}}$ is a correction due to the Earth matter effect. Independently of value of $f_{\text{reg}}$, this equation along with inequality (15) leads to

$$F_{\nu_e} \geq F_0^x,$$

which is exactly what we see in (10). Thus, accounting for the Earth matter effect does not influence our conclusion that NL case is excluded.

Let us summarize the results. If one interprets 5 LSD events on February, 23, 1987 as a detection of the electron neutrino flux from the first stage of the two-stage Supernova collapse, one comes to the following conclusions concerning neutrino properties and original (anti-) neutrino fluxes at the first stage of the explosion.

1. If the neutrino mass hierarchy is normal, than the case of $\theta_{13} \gtrsim 3 \cdot 10^{-2}$ is excluded.
2. Original $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$ and $\bar{\nu}_\tau$ fluxes are less or equal to the electron antineutrino flux at the Earth up to the obvious factor $R^2/R_{\text{ns}}^2$, see eqs.(11),(14).
3. Original electron neutrino flux is three times larger than electron neutrino flux at the Earth (up to the factor $R^2/R_{\text{ns}}^2$), see eqs.(12),(14).
4. In the case of $\theta_{13} \lesssim 3 \cdot 10^{-3}$ original electron antineutrino flux is of order of the electron antineutrino flux at the Earth (up to the factor $R^2/R_{\text{ns}}^2$), see eq.(14).

The first conclusion is of particular interest, especially regarding that if the neutrino mass hierarchy is inverted, large values of the mixing angle, $\theta_{13} \gtrsim 3 \cdot 10^{-2}$, are disfavored by the combined KII and IMB data on the second neutrino signal from SN1987A [14]. Accordingly, the total bulk of data on the SN1987A neutrino burst disfavors $\theta_{13}$ larger than $3 \cdot 10^{-2}$ whatever the mass hierarchy is.

The last three conclusions constrain any model of the SN1987A two-stage collapse. In particular, the second and the fourth conclusions are consistent with the model of the first stage of the SN1987A explosion by Imshennik and Ryazhskaya [1], while the third one contradicts it.

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