78,785

CUPP-88-3

CUPP/88-3
SINP/TNP/88-5

Does the neutrino signal from the SN 1987A indicate the existence of mass and mixing ?

ROUTE TO
NAME | LOCATION
RETURN TO

Kamales Kar
Saha Institute of Nuclear Physics
92 Acharya Prafulla Chandra Road
Calcutta 700 009, INDIA

and

Amitava Raychaudhuri
Department of Pure Physics, University of Calcutta
92 Acharya Prafulla Chandra Road
Calcutta 700 009, INDIA

ABSTRACT

The SN 1987A events observed at the KAMIOKA and IMB experiments are compared with model predictions incorporating realistic supernova neutrino luminosities along with neutrino mass and mixing.

March 1988

FERMILAB
APR 26 1988
LIBRARY

The neutrinos detected by the IMB [1] and Kamiokande II [2] collaborations from the Supernova 1987A in the Large Magellanic Cloud (LMC) on the one hand confirms the important role played by the neutrinos in the explosion and subsequent radiation of energy and on the other hand gives a rare opportunity to extract information about neutrino masses and mixings. The initial attempts concentrated on obtaining, in a model independent fashion, mass limits on neutrinos using delays for the 11 KAMIOKA events in the 12.4s pulse (more often the 8 events in the first 2s) and the 8 IMB events in the 5.6s pulse. In this manner no reliable constraints better than the current laboratory limits ($m_\nu \approx 20$ eV) resulted [3]. The other efforts used realistic neutrino luminosities calculated using detailed mechanisms of neutrino transport after the core collapse of supernovae and predicted the expected number of events in the two detectors using the SN 1987A parameters to estimate the time delays [4,5]. In this letter we combine these efforts and probe how the results using realistic luminosities change by introducing a neutrino mass and also mixing among massive neutrinos of three flavours.

Neutrino flavour mixing (and oscillation) has been attracting some attention on its own right over the last several years. The mixing of quark flavours - Cabibbo mixing and its generalisations - is an experimentally verified fact the most recent manifestation of which is the observation of B^o - $\bar{B}^o$ mixing at DESY [6]. It is natural therefore to expect the existence of mixing in the leptonic sector also. Neutrino oscillations [7] have been looked for in accelerator and reactor experiments for many years and has led to limits on their mass splitting and mixing angles [8]. The solar neutrino problem [9] can also find a solution within the same framework. It is, therefore, of interest to ask what effect, if any, it has on the neutrinos from the SN 1987A.

It is now quite clear that the time scale of the neutrino emission ($\sim$1 second <u>not</u> 1 millisecond) and the average energy of the neutrinos ($\sim$10 MeV) agree with the current supernova models of neutrinos diffusing out of a hot, opaque, protoneutron star [10]. But the somewhat long timespan of the events and the correlation of the time sequencing of the neutrinos with their energies motivated people to look for the possible effects of mass and mixing. The number of events being small it is proper to look at the cumulative number of events $N_d(t)$ as a function of time. To calculate this quantity

one must fold the luminosities of the different neutrino and antineutrino types with their corresponding cross-sections for interaction with the detector material to estimate the probability of observation. For the energies of interest, the $\bar{\nu}_e$ - p cross-section ($\bar{\nu}_e\, p \rightarrow e^+\, n$) dominates by more than two orders of magnitude over all other processes. The luminosities of the different species being of the same order it is a good approximation to retain only this process in our calculation. We thus find

$$N_d(t) = (N_p/4\pi R^2) \int_0^t dt' \int_0^\infty d\epsilon \; \frac{dN_0(\epsilon, t')}{d\epsilon} \; \sigma(\epsilon)\, \eta(\epsilon) \qquad (1)$$

where N_p is the number of protons in the detector, R the distance of LMC and $\sigma(\epsilon)$ the cross-section for the $\bar{\nu}_e$- p process of neutrinos of energy ϵ. $dN_0(\epsilon, t')/d\epsilon$ is the differential $\bar{\nu}_e$ number luminosity and $\eta(\epsilon)$ is the detector efficiency.

Eq.(1) is derived under the assumption of massless neutrinos. If instead the neutrino has a mass m then the time gap between its emmission at the SN 1987A (t_s) and its observation on earth (t_e) is

$$t_e - t_s = (R/c)/(1 - m^2/\epsilon^2)^{1/2} \approx (R/c)(1 + m^2/2\epsilon^2) \qquad (2)$$

When flavour mixing is present, the mass eigenstates λ_i with masses m_i , (i = 1,2,3 for 3 flavours) are related to the neutrinos ν_i (i=1,2,3) through a unitary mixing matrix M.

$$\lambda_i = \sum_j M_{ij}\, \nu_j \;; \qquad \nu_i = \sum_j (M^+)_{ij}\, \lambda_j \qquad (i,j = 1-3) \qquad (3)$$

This mixing leads to the possibility of neutrino oscillations in a standard way. As an example, if at time t=0 a ν_μ is produced then at any subsequent time the state is given by

$$|\psi(t)\rangle = \sum_j (M^+)_{\mu j}\, e^{-iE_j t}\, |\lambda_j\rangle \qquad (4)$$

The probability of observing a ν_e at this time is

$$P(\nu_\mu \rightarrow \nu_e, t) = |\langle \nu_e | \psi(t)\rangle|^2 = \left| \sum_j (M^+)_{\mu j}\, (M)_{je}\, e^{-iE_j t} \right|^2 \qquad (5)$$

This type of oscillation phenomena obviously also take place for antineutrinos. This so-called vacuum neutrino oscillation is to be distinguished from resonant neutrino oscillations of the Mikhayev-Smirnov-Wolfenstein (MSW) kind [11] which we do not consider in this letter.

There is one subtlety which we must now address. Eqn.(5) has been derived assuming that the wave-function remains a coherent superposition [see eq.(4)] after the time t. This, in fact, sets a limit to the range of validity of eqns.(4) and (5) [12]. Due to their mass difference, the $|\lambda_j\rangle$'s in eq.(4) will separate from each other with the passage of time. Eqs.(4) and (5) can be safely applied only so long as this separation is smaller than the size of the initial neutrino wave-packet. For the neutrinos from the SN 1987A this is <u>not</u> the case. The neutrino energy ϵ is typically $\sim$ 10 MeV. For neutrinos of mass in the eV range $p \approx \epsilon$ and $\Delta x \sim \hbar/\Delta p \sim 2 \times 10^{-12}$cm. For a rough estimate of the separation, d, between two mass eigenstates we choose m_1 = 10 eV, m_2 = 5eV and ϵ = 10 MeV. Then with R = 1.7 x 10^{23} cm we get from eq.(2) $d = R\,(m_1^2 - m_2^2)/2\,\epsilon^2 \approx 6\times10^{10}$cm. Thus $d \gg \Delta x$ and we must consider the neutrinos to be an incoherent mixture of the λ_j when they arrive. (Note that even if Δx is chosen to be as large as the size of the core of the supernova – $\sim$100 km - still this conclusion remains valid). We must therefore replace the coherent superposition in eq. (5), for example, by the incoherent one :

$$P(\nu_\mu \to \nu_e, t) = \sum_j \left| (M^\dagger)_{\mu j}\, (M)_{je}\, e^{-iE_j t} \right|^2 \qquad (6)$$

It is straight-forward to incorporate the effect of neutrino mass and mixing into eq. (1). We now obtain -

$$N_d(t) = (N_p/4\pi R^2) \sum_{i=e,\mu,\tau} \sum_{j=1}^{3} |M_{je} M^*_{ji}|^2 \int_0^\infty d\epsilon \, \frac{dN^i(\epsilon)}{d\epsilon}\, \sigma(\epsilon)\, \eta(\epsilon)$$
$$\cdot \int_0^t dt_e\, f^i\left(t_e - R/[1 - m_j^2/\epsilon^2]^{1/2}\right) \qquad (7)$$

In writing eq.(7) we have assumed the differential number luminosity for the ith neutrino flavour to be in a factorised form with its energy dependence determined by $dN^i(\epsilon)/d\epsilon$ and its dependence on the time t_s (at the supernova) fixed by the functions f^i.

In our calculations we have considered two supernova models based on $15M_\odot$ and $12M_\odot$ stars. The time dependence of the neutrino luminosities - the functions f^i - are obtained from Mayle [13]. The energy distribution $dN^i/d\epsilon$ is known to be Fermi-Dirac to a good accuracy and in line with the expectations [5] we choose the temperature to be 5MeV for $\bar{\nu}_e$ and 6MeV for $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$.

As already mentioned we retain only the dominant $\bar{\nu}_e p \to e^+ n$ reaction in our work for which the cross-section is given by $\sigma(\epsilon) = (0.89 \times 10^{-41} cm^2) \times (\epsilon / 10\ MeV)^2$. If we neglect CP-violation in the neutrino sector then the mixing matrix M is orthogonal. In analogy with the empirical form of the quark mixing matrix we choose it to be of the form

$$M = \begin{pmatrix} 1-\lambda^2/2 & -\lambda & 0 \\ \lambda & 1-\lambda^2/2 & \lambda^2/2 \\ 0 & -\lambda^2/2 & 1 \end{pmatrix} + O(\lambda^3) \qquad (8)$$

where λ is the analogue of $\sin\theta_c$, θ_c being the Cabibbo angle. The distance of the LMC is not known precisely ; we choose $R = 1.7 \times 10^{23} cm \approx 54.9$ kpc [3].

Our results for the KAMIOKA and IMB detectors are shown in Figs 1a and 1b. For KAMIOKA (IMB) we take $N_p = 1.4 \times 10^{32}$ (2.2×10^{32}) and $\eta(\epsilon) = \{1 - \exp[-(\epsilon/8.5\ MeV)^3]\}$ $(\{1 - \exp[-(\epsilon/34\ MeV)^{3.1}]\})$

which are known to be in good agreement [14] with the published values of these groups. We have also shown in the figures the cumulative observed events at the two detectors. For the KAMIOKA sample we have excluded their sixth event with very low energy. In both Fig 1a and 1b we have plotted three sets of curves for each supernova model : one for a massless $\bar{\nu}_e$ (dot-dashed lines), another for a $\bar{\nu}_e$ of mass 5eV (broken lines) and a third (solid lines) for a three flavour model with mass eigenvalues 5, 10 and 20eV and with the mixing parameter λ (see eq.8) chosen to be 0.5. There is one issue which perhaps needs clarification : The zero of time of the detector and those of our calculation are not related and on the face of it can be chosen arbitrarily. It originates from the difficulty in comparing a discrete observational data with a continuous theoretical prediction. We use a procedure employed in similar cases in nuclear physics [15] and fix the zero of time at the point where the first event is detected and where the continuous predictions reach the value 0.5.

From the figures it is evident that the 12 $M_\odot$ model is closer to the data for both KAMIOKA and IMB. Further, the introduction of a 5eV $\bar{\nu}_e$ mass changes the prediction at small times only and is not of much significance. On the other hand the three neutrino model with mass and mixing is strikingly closer to the data in every case. For the $15 M_\odot$ model the massless $\bar{\nu}_e$ prediction is consistently well above the observed data while the introduction of mass

with mixing moves it in the right direction by a fair amount. In the 12 $M_\odot$ case for the IMB detector (Fig.1b) the three neutrino model with mixing is clearly closest to the data while for KAMIOKA (Fig.1a) it is also perhaps the best - especially for the longer times - though all three curves are in fair agreement.

The physics behind this result can be understood in simple terms from a consideration of the supernova neutrino luminosities, $L_{\bar{\nu}}$. According to Mayle [13] the time distribution of the different $L_{\bar{\nu}}$ are all approximately of the following nature : There is a peak in the distribution in the first 0.5s beyond which it remains fairly constant. Furtheremore, for the 15 $M_\odot$ model $L_{\bar{\nu}_e}$ is higher than $L_{\bar{\nu}_\mu}$ for the entire duration while for $12M_\odot$ this is true initially but asymptotically $L_{\bar{\nu}_\mu} > L_{\bar{\nu}_e}$. In every case $L_{\bar{\nu}_\tau}$ is the same as $L_{\bar{\nu}_\mu}$, of course. Due to mixing between neutrino flavours, part of the $\bar{\nu}_e$ will be lost as $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ while some initial $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ will register at the detector as $\bar{\nu}_e$. The net effect of mixing will thus be to replace the pure $\bar{\nu}_e$ luminosity by an admixture of $L_{\bar{\nu}_e}$, $L_{\bar{\nu}_\mu}$ and $L_{\bar{\nu}_\tau}$ determined by the mixing parameter λ. However, one cannot immediately relate these $L_{\bar{\nu}}$ distributions to the calculated curves due to the time delay which depends on the neutrino energy. For IMB the threshold is rather high (34 MeV) and for neutrinos with masses of order 10eV the delay is less than 0.3s according to eq.(2). Thus over the 3s period which we examine (Fig.1b) this delay is of no great consequence. Therefore in this case the behaviour of the calculated distributions tallies rather well with our expectations discussed earlier. For KAMIOKA the threshold is lower (8.5 MeV) and the time delay can be as large as 4s. While asymptotically the behaviour is again in agreement with the simple minded expectations the initial behaviour is more complicated.

A few remarks are now in order. In an earlier work [16] it was shown that in supernova models with shock regeneration through delayed neutrino heating, the luminosity played a sensitive role. In this analysis also it is found to be of primary importance and it underscores the necessity of a careful calculation of this quantity.

We have only considered vacuum neutrino oscillations ignoring the MSW [11] resonant oscillations which have been found useful in resolving [17] the solar neutrino problem. It may be relevant to recall that for our work the oscillation must be between antineutrinos for significant effect while for the solar case it has to be among neutrinos. The MSW mechanism can admit only one or the other but not both simultaneously.

In conclusion, we find that the neutrino data from the SN 1987A is better reproduced by the realistic neutrino luminosities for a $12M_\odot$ model than for a 15 $M_\odot$ one. The incorporation of a 5eV $\bar{\nu}_e$ mass has no significant effect while a three flavour model with mass and mixing is in much better agreement with the data. Needless to say, however, the number of events is rather small and the conclusions drawn from them are necessarily tentative.

Acknowledgements :

We thank Bhaskar Datta and Alak Ray for helpful discussions and correspondence. We are grateful to J.Chatterjee for computational help. The work of A.R. is supported in part by the University Grants Commission, India and the Indian National Science Academy.

References

1. R. M. Bionta et al., Phys. Rev. Lett. 58 (1987) 1494.
2. K. Hirata et al., ibid 58 (1987) 1490.
3. E.W. Kolb, A.J.Stebbins and M.S.Turner, Phys. Rev. D35 (1987) 3598 and references therein. See also N.D.Hari Dass, D. Indumathi, A.S.Joshipura and M.V.N.Murthy, Inst. of Math Sciences preprint IMSc/TP/87/001.
4. S.W.Bruenn, Phys. Rev. Lett. 59 (1987) 938.
5. A. Burrows and J. M. Lattimer, Steward Observatory, Arizona preprint No.725.
6. H. Albrecht et al., Phys. Lett. 192B (1987) 245.
7. B. Pontecorvo, Sov. Physics JETP 6 (1958) 429 ; S.M.Bilenky and B.Pontecorvo, Phys. Rep. 41 (1978) 225.
8. J. Bofill et al, Phys. Rev. D36 (1987) 3309; L.A.Ahrens et al., ibid D31 (1985) 2732 ; F.T.Avignone et al., Phys. Rev. Lett. 50 (1983) 721.
9. R. Davis, Phys. Rev. Lett. 12 (1964) 303; J.N.Bahcall et al., Ap.J. 292 (1985) L79.
10. A. Burrows and J.M.Lattimer, Ap. J. 307 (1986) 178.
11. S.P.Mikheyev and A. Yu. Smirnov, Il Nuovo Cimento 9C (1986) 17 ; L. Wolfenstein, Phys. Rev. D17 (1978) 2369.
12. B. Kayser, Phys. Rev. D24 (1981) 110.
13. R. W. Mayle, Ph.D. thesis, UCRL - 53713 (unpublished).
14. L. M. Krauss, Yale preprint YTP 87-16.

15. K. F. Ratcliff, Phys. Rev. C3 (1971) 117 ; S. Sarkar, K. Kar and V.K.B. Kota, ibid C36 (1987) 2700.

16. A. Ray and K. Kar, Ap. J. 319 (1987) 143.

17. H. A. Bethe, Phys. Rev. Lett. 56 (1986) 1305.

Figure Caption

The KAMIOKA (Fig.1a) and IMB (Fig.1b) data compared with the theoretical predictions based on 12 $M_\odot$ and 15 $M_\odot$ models. The solid lines correspond to a three neutrino model with mixing (see text). The dot-dashed (broken) lines are for a no mixing situation with a massless (mass = 5eV) electron neutrino.

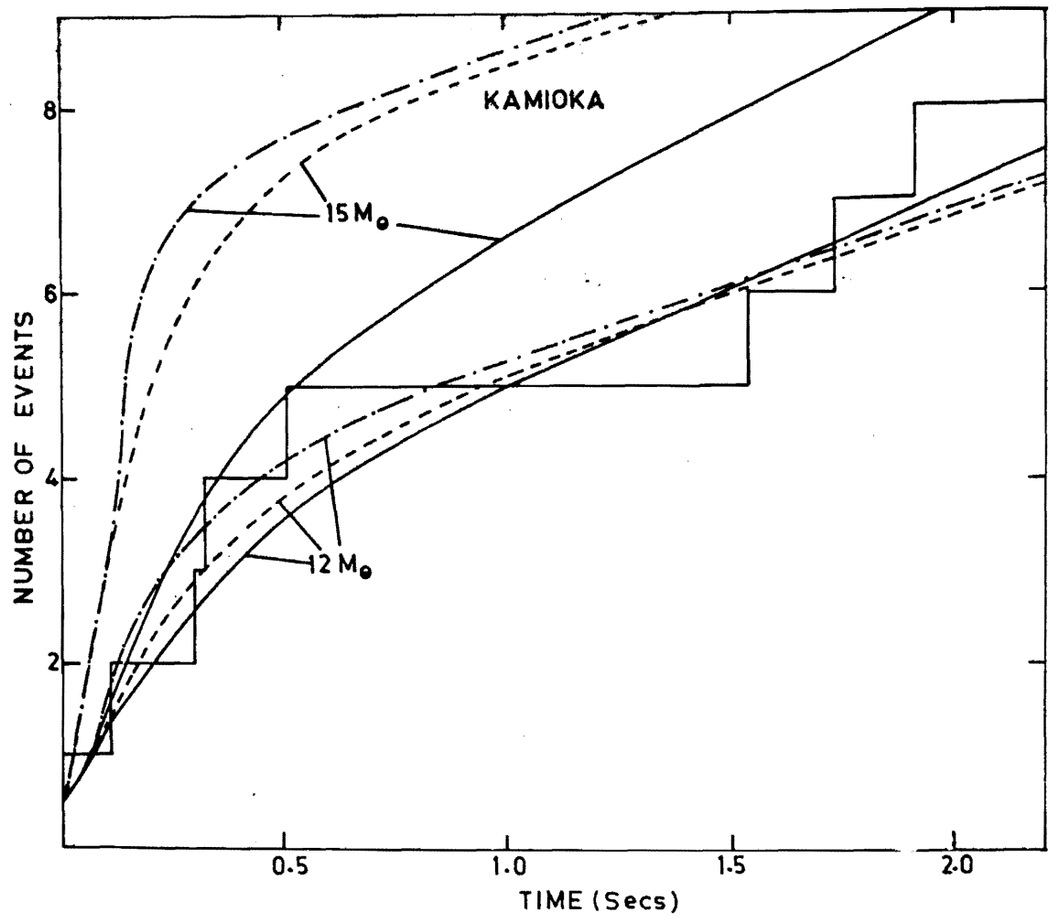

Fig.1a

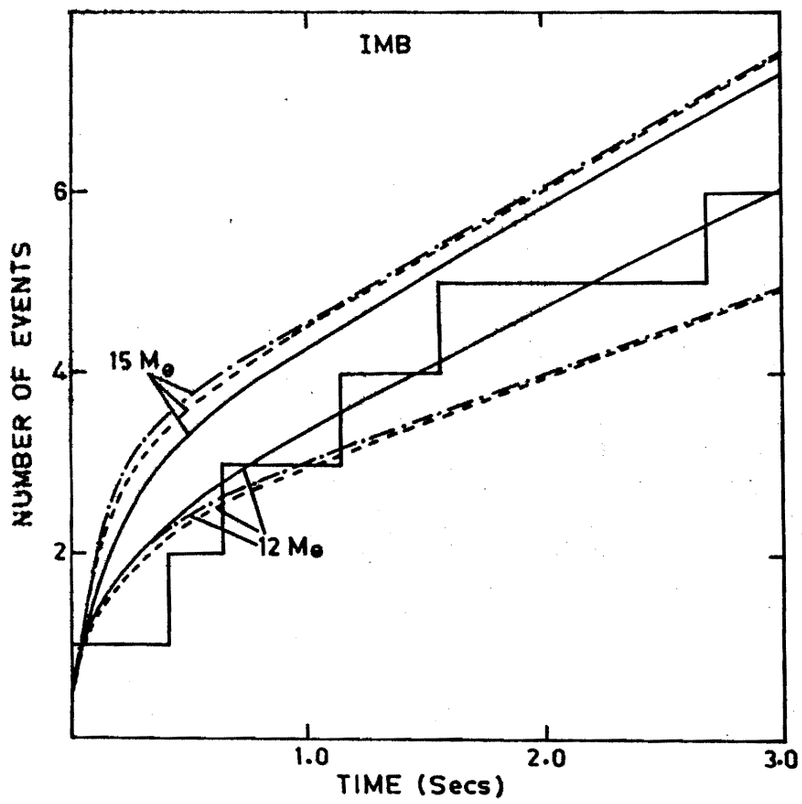

Fig.1b