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Brief Reports

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Remarks on the first two events in the supernova burst observed by Kamiokande II

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We examine the possibility, remote but not totally improbable, that one of the first two supernova events observed in the Kamiokande II detector consists of an electron neutrino scattering from an electron. From arguments of timing we show that this possibility can be realized only for the first event, and that it requires the electron-neutrino mass to be less than 2.5 eV. The occurrence of such an event means that, of the various Mikheyev-Smirnov-Wolfenstein solutions to the solar-neutrino problem, the nonadiabatic one is likely to be correct.

The first two events in the supernova burst[1,2] observed in the Kamiokande II detector[1] (KII) point back to the Large Magellanic Cloud, and so it is possible to interpret at least one of them as a neutrino-electron scattering reaction. Here we examine the implications of such an interpretation for Mikheyev-Smirnov-Wolfenstein (MSW) solutions[3] of the solar-neutrino problem, taking into account general questions of the relative timing of events and of neutrino mass.

In general, the neutrino scattered by an electron in the KII detector can be a particle or an antiparticle of any flavor and so it is hard to tell whether an oscillation between flavors has, or has not, taken place. The general theory of supernova explosions,[4–6] however, indicates that the initial, deleptonizing emission consists solely of electron neutrinos from electron capture on protons; and the standard electroweak model tells us that the electron neutrino ν_e has the largest electron scattering cross section of all neutrino types.[7] Therefore, if we can identify one of the earliest events as neutrino-electron scattering, then there is a good chance that it is induced by a deleptonizing ν_e. This represents our best hope of identifying the neutrino that induces the scattering process.

This identification carries with it implications for the MSW effect and also for the timing of the early events in the KII burst. If the neutrino responsible for one of the first two events comes from the deleptonizing phase, then it must be emitted before the neutrinos responsible for later events in the KII detector. As we shall see, satisfying this condition imposes limits on the neutrino mass and fixes the order of emission of the first two events.

With these ideas in mind, we consider the possibility that the first event is indeed $\nu_e e \rightarrow \nu_e e$. The occurrence of one such event in a sample of 11 events is not highly likely: the theoretical expectation is about 0.07 $\nu_e e$ events[5,6] and from Poisson statistics the probability for one event is 6.5%. An alternative interpretation, namely, that the event is inverse β decay ($\bar{\nu} p \rightarrow n e^+$) with the positron contained in a 15° cone about the forward direction, is somewhat more likely: the expectation is 0.17 such events and the probability for one is 14%. But, with the meager statistics available, we cannot discount the possibility of large fluctuations around the expected distributions, and so we shall pursue the $\nu_e e$ scattering interpretation.

For our purposes, the essential problem of νe scattering is to infer the energy of the incident neutrino E_ν from the observed properties of the scattered electron (see Table I). In principle, the kinematics of νe scattering allow us to determine E_ν from the observed kinetic energy T_e and the scattering angle ϕ of the recoil electron; but in practice, this is not a reliable method. For one thing, we have to appeal to the large errors on ϕ to ensure that the angle falls within the allowed kinematic range ($\cos\phi > [T_e/(T_e+2m_e)]^{1/2}$ implies that $\phi < 15°$ for $T_e = 13.5$ MeV and $\phi < 12°$ for $T_e = 23$ MeV); and for another, the expression for E_ν contains the factor $\{\cos\phi - [T_e/(T_e+2m)]^{1/2}\}$ in its denominator and hence is very sensitive to small changes in the scattering angle. We must therefore find another method of estimating E_ν.

The approach we take is to calculate the average recoil energy $\langle E_e \rangle$ of scattered electrons in terms of the energy E_ν and flavor of the incident neutrino.[8] We then assume that each observed electron energy is close to its average value appropriate to the energy of the incident neutrino, and then infer the neutrino energy from the relationship between $\langle E_e \rangle$ and E_ν.

TABLE I. Characteristics of the first five supernova events observed in the KII detector (Ref. 1).

Event	Time (msec)	Electron energy (MeV)	Electron angle (Degrees)	Estimated neutrino energy (MeV) $\nu_e \to \nu_e$	$\bar{\nu}p \to ne$
1	0	20 ±2.9	18±18	40	21.5
2	107	13.5±3.2	15±27	27	15
3	303	7.5±2.0	108±32		9
4	324	9.2±2.7	70±30		11.7
5	507	12.8±2.9	135±23		14.3

For incident electron antineutrinos $\bar{\nu}_e$, $\langle E_e \rangle$ is approximately $\frac{1}{3}$ of E_ν, and for all other types $(\nu_e;\nu_\mu,\bar{\nu}_\mu;\nu_\tau,\bar{\nu}_\tau)$ it is approximately $\frac{1}{2}$ of E_ν. The difference arises from the charged-current diagram which makes the $(V-A)$ component in $\bar{\nu}_e e$ scattering much stronger than in other types of νe scattering. From this argument, we infer that the first neutrino has an energy of 40 MeV. It should be kept in mind that because the y distribution in $\nu_e e$ scattering is almost flat, this is necessarily a crude estimate of the neutrino energy, and that it could easily be wrong by 5–10 MeV. For our purposes, a variation by this amount is not significant.

Let us now consider the implications of identifying the first neutrino as a ν_e with energy 40 MeV for the various MSW solutions to the solar-neutrino problem.[3] It has been pointed out by Walker and Schramm[6] that in their passage through the material of a type-II supernova, neutrinos will traverse a region with density profile much like that of the Sun. They will therefore be subject to the same matter-enhanced oscillation effects as are solar neutrinos, and they will be affected by the different MSW solutions in different ways.

In the adiabatic solution discussed by Bethe,[9] the mass difference Δm^2 is approximately 10^{-4} eV^2, and the adiabatic condition for neutrinos in the 20–50-MeV energy range is satisfied as long as $\sin^2 2\theta \geq 10^{-2}$. Computations of the probability for ν_e to remain ν_e indicate that neutrinos in this energy range are almost totally converted from ν_e to ν_μ (or ν_τ). Now the ν_μ (or ν_τ) cross section for νe scattering is smaller than that for ν_e by a factor of 7 (Refs. 6 and 7), and hence the likelihood that the first event is νe scattering is reduced by a corresponding amount as long as the incident neutrino comes from the initial deleptonizing burst. Therefore, barring some unexpected fluctuation, we conclude that the identification of the first neutrino in the KII burst as an electron neutrino ν_e which undergoes νe scattering is in conflict with the adiabatic MSW solution.

In the nonadiabatic solution discussed by Rosen and Gelb,[10] mass differences are generally smaller than 10^{-4} eV^2 and obey the condition $(\Delta m^2)\sin^2 2\theta \approx 10^{-7.5}$. Computed probabilities indicate that for energies of 20–50 MeV the probability for ν_e to remain ν_e is roughly 0.7 or higher. Thus the nonadiabatic solution gives a high probability that the first neutrino is a ν_e.

Finally, in the large-mixing-angle case of Parke and Parke and Walker,[11] neutrinos of all energies have the same probability for ν_e to remain ν_e, namely, about 0.3. We may therefore conclude that if the first neutrino is a ν_e which undergoes νe scattering in the KII detector, then the nonadiabatic MSW solution is most likely to be correct.

The small mass differences associated with the MSW effect provide us with two broad options for the neutrino masses themselves: either they are comparable with the mass differences, or they are much greater. In the former case the masses are of order 10^{-3} eV and the neutrinos travel, for all practical purposes, with the speed of light; in the latter case, neutrinos of different flavors are highly degenerate in mass and differences in their speeds, at fixed energy, are negligible.

We next consider the timing of the first neutrino in relation to others in the burst, especially those arriving at KII within the first 500 msec (see Table I). By assuming that it is a deleptonizing ν_e, we are requiring that the order of arrival reflect the order of emission from the supernova. Dar and Dado[12] have observed that this requirement sets an upper bound on the electron-neutrino mass: for, were the mass too large, the third, fourth, and fifth neutrinos, which tend to be less energetic than the first one, would travel so slowly that they would have to have been emitted before the first one, clearly contradicting our basic assumption.

Now the general time structure[5,6,13] of the deleptonizing neutrinos ν_e appears to consist of an initial burst which carries away roughly $\frac{1}{3}$ of them within a time of order 3 msec, an intermediate stage during which the "thermal" neutrinos begin to bulk up, and a final stage during which the thermal neutrinos are dominant. The time scale for the intermediate stage is of order 100 msec, and that for the final stage is seconds.

Because of the relatively large scattering angles in events 3, 4, and 5, we assume that they are inverse β decays engendered by electron antineutrinos from the thermal emission, which contains all varieties of neutrino in comparable proportions.[5,6] Therefore the third, fourth, and fifth neutrinos must have been emitted from the supernova at least 100 msec after the first one. This requirement, together with the arrival times and estimated neutrino energies in Table I, leads to an upper bound of 2.5 eV on the mass of the electron neutrino: if the actual mass of ν_e falls below this bound, then it is kinematically possible for the first neutrino to have been emitted 100 msec before the others; and if it exceeds the bound, then it is not possible. For the purposes of the following discussion we assume that the mass is less than the bound.

The next problem we confront is the nature of the second event and its timing relative to the first one. If, as is more likely, it is an inverse β decay, then the energy of the second neutrino is about 15 MeV and it must be emitted from the supernova at least 40 msec after the first neutrino; thus it would fall comfortably within the buildup stage of the thermal emission. If, on the other hand, the event is neutrino-electron scattering, then according to our prescription the energy of the second neutrino is 27 MeV and we must consider several alternatives for its identity and time of emission. In this connection, we note that the probability for two scattering events out of eleven is smaller than that for two inverse β decays with forward going positrons, being 2×10^{-3} as compared with 12×10^{-3}; nevertheless we consider the possibility of scattering.

For the second neutrino to be another deleptonizing ν_e emitted within a few milliseconds of the first one, the mass of the electron neutrino would have to be 7 eV, far in excess of our bound. Consequently the second neutrino is more likely to come from the thermal stage and, once the cross sections and relative abundances of the several neutrino types are taken into account,[6] the probability for its being not ν_e is about the same as for ν_e. The ν_e option and the 2.5-eV mass limit imply that the second neutrino must be emitted at least 95 msec after the first one; the not ν_e option could, in principle, lead to a much smaller time interval, but if we use MSW to argue that masses or mass differences are very small, then it too yields an emission time interval close to 100 msec. This means that we cannot identify the flavor of the second neutrino, even if it does undergo neutrino-electron scattering.

So far we have worked with the assumption that the first event observed in KII is a neutrino-electron scattering induced by a deleptonizing ν_e, and we have found that in such a scenario the neutrino responsible for the second event must belong to a later phase of the supernova emission. Suppose now that we were to repeat the analysis using the alternative assumption that the second event is induced by a deleptonizing ν_e which is emitted before all the other neutrinos observed in KII. We would then find that the timing requirement leads to contradictory constraints on the mass of the electron neutrino: for the neutrinos associated with events 3, 4, and 5 (see Table I) to be emitted later, the mass must be less than 1.8 eV, whereas for the neutrino associated with the first event to start later than the one associated with the second, the mass must be greater than 7 eV. Therefore our alternative assumption about the second event cannot be maintained.

We can summarize our findings by saying that, of the first two events in the KII detector, only the first has the possibility of being induced by an electron neutrino from the initial phase of the supernova burst; the second neutrino belongs to a later phase. A necessary condition for this possibility to be realized is that the neutrino mass be less than 2.5 eV. Therefore, even though we may never be able directly to decide the origin of the first event, independent measurements of the neutrino mass may give us a clue.[14]

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