Neutrino Mass Limits from SN1987A

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A neutrino signal from the supernova SN1987A is used to place an upper limit on the neutrino mass. If most of the neutrinos must have been emitted within several seconds, as suggested by astrophysical models, the last three of the eleven events observed by the Kamioka detector must correspond to noise or to the tail of a distribution in emission times. If the remaining eight events (which arrived within two seconds of one another) are due to neutrinos emitted within four seconds (a conservative upper limit), the bound $m_{\nu_e} \leq 12$ eV/c^2 is obtained. The Irvine-Michigan-Brookhaven data, with a higher energy threshold, primarily provide information regarding the total duration of the burst.

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The first optical record of the supernova SN1987A[1] occurred at 10:37:55 UT on 23 February 1987.[2] About three hours earlier, a neutrino signal was observed nearly simultaneously at the Kamioka[3] and IMB (Irvine-Michigan-Brookhaven)[4] detectors:

23 February, 7:35:35 UT (± 1 min) (Kamioka),

23 February, 7:35:41 UT (IMB).

A pulse observed at 2:52 UT on the same day by a detector in the Mont Blanc tunnel[5] was not confirmed by the much larger Kamioka or IMB detectors and thus does not appear to have been due to neutrinos.

The Kamioka detector's low energy threshold permits neutrinos with a range of energies to be detected. In this note we use this feature to place limits on the electron neutrino's mass,[6] under simple assumptions about the time structure of the emission process. A thorough analysis of the time profile of neutrino emission from a supernova should be able to improve upon these bounds somewhat, but we wish to avoid at this early stage conclusions based on any specific models.[7]

The IMB detector's energy thresholds appear to be higher than those at Kamioka. Furthermore, there is a question of the relative synchronization of the clocks in the two experiments. Consequently, IMB data in the present analysis primarily provide a constraint with respect to the total duration of the neutrino burst.

The distance to the supernova is 52 ± 5 kpc,[8] corresponding to a light travel time t_0 of

$$t_0 = (5.3 \pm 0.5) \times 10^{12}\ \text{s}. \qquad (1)$$

A neutrino of mass m and energy E will take a total time of

$$t_{\text{obs}} - t_{\text{em}} = t_0(1 + m^2/2E^2) \qquad (2)$$

to reach the Earth. The observation times t_{obs} and neutrino energies E are shown in Tables I and II.[3,4] We have assumed for present purposes that all events are due to $\bar{\nu}_e p \rightarrow e^+ n$, so that $E \simeq E_e + m_n - m_p +$ (small recoil correction), where the recoil correction is estimated from the quoted electron angle with respect to the source.[3] We may infer emission times t_{em} as a function of m^2 for each event, noting that m^2 need not be the same for all events. Indeed, neutrinos of various species are expected from supernovae.[9,10]

The values of t_{em} obtained from the Kamioka data via Eq. (2) (with a constant value of t_0 subtracted) are shown as functions of m^2 in Fig. 1. Two lines are shown for each event, corresponding to energies at the upper and lower limits of the errors in Table I. The value $t_{\text{em}} = 0$ corresponds to the time at which the first detect-

TABLE I. Observation times and inferred neutrino energies in the Kamioka experiment.

Event No.	t_{obs} (s)	Energy (MeV)
1	0 (def)	21.3 ± 2.9
2	0.107	14.8 ± 3.2
3	0.303	8.9 ± 2.0
4	0.324	10.6 ± 2.7
5	0.507	14.4 ± 2.9
6[a]	0.686[a]	7.6 ± 1.7[a]
7	1.541	36.9 ± 8.0
8	1.728	22.4 ± 4.2
9	1.915	21.2 ± 3.2
10	9.219	10.0 ± 2.7
11	10.433	14.4 ± 2.6
12	12.439	10.3 ± 1.9

[a] Event 6 was excluded from the analysis of Ref. 3 because it had fewer than 20 photomultiplier hits.

TABLE II. Observation times and inferred neutrino energies in the IMB experiment.

Event No.	t_{obs} (s)	Energy (MeV) (±25%)
1	0 (def)	39
2	0.42	38
3	0.65	41
4	1.15	36
5	1.57	30
6	2.69	38
7	5.01	21
8	5.59	25

ed neutrino would have been emitted if it were massless. For events 1 and 2, compatible with neutrino-electron as well as neutrino-nucleon scattering by virtue of their particularly small angle with respect to the source, the neutrino energies are likely to be larger than those quoted in Table I, as a result of the substantial electron recoil possible. For larger neutrino energies, the corresponding slopes in Fig. 1 for events 1 and 2 should be shallower.

The first feature of Fig. 1 that strikes the eye is the tendency of events to cluster in time with one another. This tendency, visible for small m^2, is lost as m^2 increases. This will serve as a basis for upper limits on neutrino mass. Current models of supernovae[9,10] suggest that they emit neutrinos in a short pulse of 1–2-s duration. Events 10–12 are not consistent with this hypothesis, if any single value of m^2 describes all the Kamioka events.

Let us first assume that the astrophysical models can accommodate emission times such that events 1–12 (excluding No. 6) all came from the supernova. In Fig. 1(a), the shaded lines denote the boundaries of the smallest time interval containing all events. As seen in Fig. 2, this time interval $\Delta t_{\min}$ is never less than about 10 s. It begins to grow appreciably for $m_\nu \gtrsim 23$ eV/c^2. If we demand that the emission times coincide to within 15 s, we obtain the bound

$$m_\nu \lesssim 27\ \mathrm{eV}/c^2 \quad (\Delta t_{\min} \lesssim 15\ \mathrm{s}), \tag{3}$$

if all events are due to neutrinos of the same mass.

There may be reasons for excluding events 10–12 from our analysis. Their great separation from the rest of the events and their relatively low energies suggest a somewhat higher probability that they are noise than the rest of the signal. We consider this possibility open pending further analysis by the Kamioka group.

A second possibility is that events 10–12 could be associated with a "late burst" of the supernova[11] or a long tail of the distribution in emission times. In present models,[10] such tails do extend over tens of seconds, but over half the energy in $\bar{\nu}_e$ is expected to arrive in the first two seconds. The late events might then be irrelevant for precise time-of-flight studies.

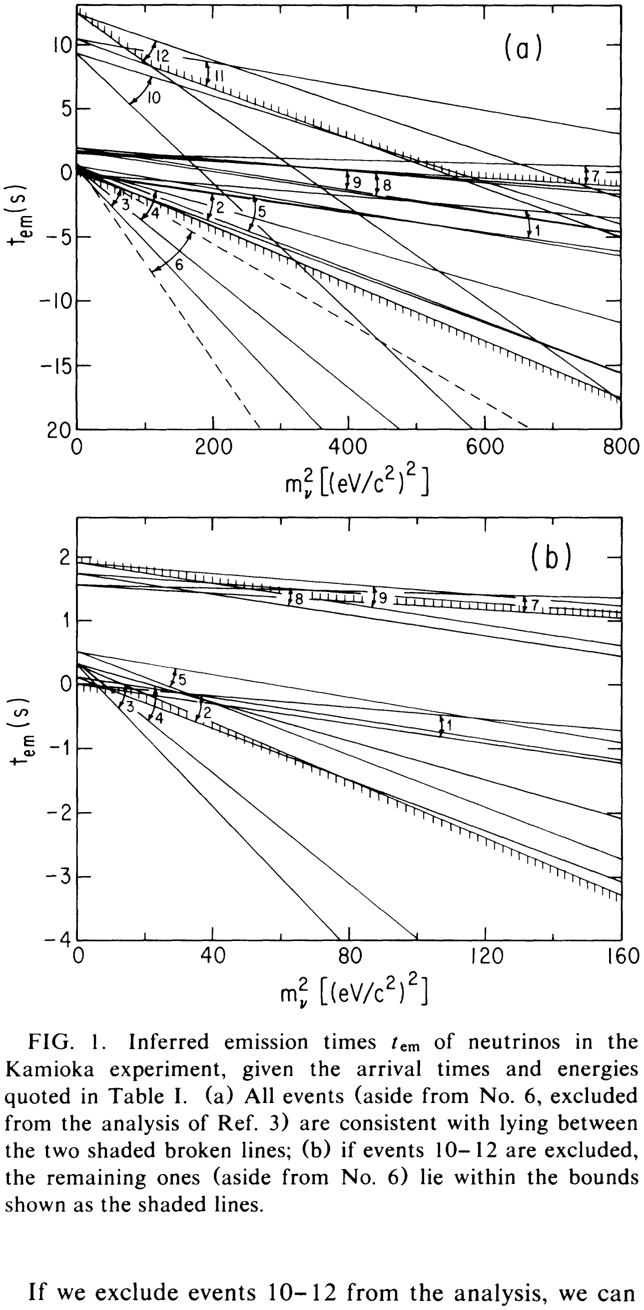

FIG. 1. Inferred emission times t_{em} of neutrinos in the Kamioka experiment, given the arrival times and energies quoted in Table I. (a) All events (aside from No. 6, excluded from the analysis of Ref. 3) are consistent with lying between the two shaded broken lines; (b) if events 10–12 are excluded, the remaining ones (aside from No. 6) lie within the bounds shown as the shaded lines.

If we exclude events 10–12 from the analysis, we can determine the minimum time interval $\Delta t_{\min}$ over which the remaining events could have been emitted. This interval is bounded by the shaded lines in Fig. 1(b), and is plotted as the dashed line in Fig. 2. The interval grows rapidly from less than two seconds for $m^2 = 0$, behaving as

$$\Delta t_{\min} \simeq \{1.24 + 1.93[m_\nu/(10\ \mathrm{eV}/c^2)]^2\}\ \mathrm{s} \tag{4}$$

for $m_\nu \gtrsim 8.6$ eV/c^2. It is then based on events 3 and 7, which have the lowest and highest energies in the sample. For $\Delta t_{\min} \lesssim 4$ s (our estimate of the upper limit al-

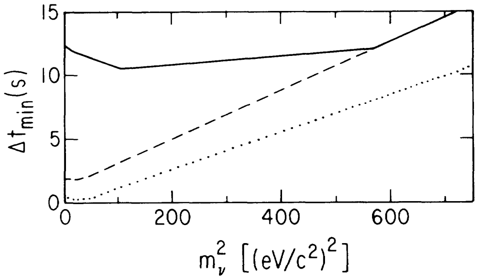

FIG. 2. Minimum time interval $\Delta t_{\rm min}$ over which neutrinos could have been emitted for the Kamioka experiment as function of m^2. Solid line, all events; dashed line, excluding events 10–12; dotted line, excluding events 7–12. Event No. 6 has been excluded here.

lowed by astrophysical models), we find

$$m_\nu \leq 12\,\mathrm{eV}c^2 \;\; (\Delta t_{\rm min} \leq 4\ \mathrm{s}). \tag{5}$$

The limit (5) is more stringent than any obtained so far on the basis of any direct laboratory experiments.[12,13] Assuming that Eq. (5) indeed applies to electron neutrinos, the limit is incompatible with the claim of one group[13] for a finite electron-neutrino mass, $m_{\bar{\nu}_e} \geq 17\ \mathrm{eV}/c^2$.

A further improvement on the bound (5) is possible if one takes seriously calculations[10] which indicate the presence of an initial "pulse" of neutrinos of less than 1-s duration. Events 1–5 are candidates for such a pulse. They all would have been emitted within 1 s of one another if $m_\nu \leq 9.4\ \mathrm{eV}/c^2$, as indicated by the dotted line in Fig. 2. This bound is based on events 1 and 3, and remains valid if the neutrino energy for event 1 is greater than that shown in Table I, as one might expect if the first event is due to ν_e-e^- scattering.

The possibility exists that additional events could be due to neutrino-electron scattering, as only events 3, 5, 10, and 12 are characterized by an electron direction more than 90° (and typically $\gtrsim 3\sigma$) away from the source. The bound (5) remains valid if, for example, the neutrino energy of event 7 is higher than that shown in Table I. However, it has been estimated[9] that it is very unlikely that more than two events in the Kamioka sample could be due to neutrino-electron scattering. The first two events are the best candidates for this process.

We now turn to the IMB data. Events 1 and 8 define the minimum time interval over which all events could have been emitted:

$$\Delta t_{\rm min} \simeq \{5.59 - 0.63[m_\nu/(10\ \mathrm{eV}/c^2)]^2\}\ \mathrm{s}. \tag{6}$$

The later arrival of the last two events, which have about 15 MeV lower energy than the others, could have been construed as evidence for finite neutrino mass were it not for our previously stated arguments based on the Kamioka data. The possibility of a "late burst" or the tail of a time distribution remains open.

We have not incorporated the possibility of neutrino oscillations into our analysis, but the present data will provide useful constraints on models of such oscillations.

We expect the bound (5) to be improved once it becomes possible to incorporate the expected time structure of neutrino emission. Without detailed information on this time structure, which requires detailed multidimensional hydrodynamical calculations, it is premature to attempt a statistical analysis; simple Poisson statistics, for example, will not suffice. Our purpose in preparing this early note was to show what can and cannot be concluded from the data in as model-independent fashion as possible.

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