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Brief Reports

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Quasi-model-independent analysis of the Kamiokande-II neutrino events from SN 1987A

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An analysis of the differences in arrival times of the neutrino events observed with Kamiokande II strongly implies that the latest three events were kinematically quite different from the other events, and should not be included for the purpose of extracting bounds on $m_{\nu_e}c^2$. A maximum-likelihood analysis of the first eight events yields the following constraints: $m_{\nu_e}c^2 < 9$ eV (68% C.L.), < 14 eV (95% C.L.), and < 17 eV (99.7% C.L.). These bounds are kinematical and depend only on very general assumptions concerning the collapse and cooling processes.

Numerous analyses of the ν events from SN 1987A (Refs. 1–3) have appeared in the literature.[4–15] The following is a representative set of values or bounds placed on $m_{\nu_e}c^2$: <2.5 eV (Ref. 4), <4 eV (Ref. 5), <5 eV (Ref. 6), <11 eV (Ref. 7), <12 eV (Ref. 8), <16 eV (Ref. 9), <16 eV (Ref. 10), <26 eV (Ref. 11), $\lesssim 30$ eV (Ref. 12), 3.9 ± 0.8 eV (Ref. 13), $\simeq 22$ and 4 eV (Ref. 14), and $\simeq 30$ eV (Ref. 15).

An extensive account of the pitfalls involved in analyzing and interpreting these data is given by Kolb, Stebbins, and Turner.[12] More recently, Spergel and Bahcall[9] have critiqued several of the popular assumptions used to arrive at some of these limits. They have also carefully analyzed the temperature versus time curves of several supernova models, and concluded that such effects contribute small uncertainties, approximately ± 1 eV. They establish a model-dependent bound on the mass of ν_e. We do not discuss all previous analyses, nor do we claim completeness in our references. They only constitute a set of examples covering the interesting range of bounds on $m_{\nu_e}c^2$.

Finally, several authors[16,17] have considered the possibility that the time structure of the detected events could imply scenarios which are not contained in standard supernova models, for example, that of Mayle, Wilson, and Schramm.[18] We show that the first eight events recorded with Kamiokande II (Kam-II), allow interesting bounds on the mass of ν_e, with only minimal assumptions. These bounds are essentially the same as those from the model-dependent analysis of Spergel and Bahcall[9] or those of Burrows.[10]

The present analysis is based on several observations. First, there is no reason why the data from the two Cherenkov detectors, Kam-II, and that of the Irvine-Michigan-Brookhaven group (IMB) should be treated as a single experiment. On the contrary, the possibility that systematic errors might be quite different, dictates that they be analyzed separately. In addition, the two detectors are sensitive to different energy ranges and it should be recognized that higher-energy neutrinos can be trapped earlier in the collapsing core due to their larger interaction cross sections. This might result in spreading of the neutrino arrival times for higher-energy neutrinos. Finally, all differences in the detection times of all pairs of neutrinos and their energies, should be consistent with physically plausible ranges of ν_e mass and emission times from the core. Our analysis is based on these differences in arrival times. For 11 events, there are only ten independent arrival-time differences; however, an analysis of all 55 time differences gives information on the distribution of emission times. We use this information only in an analysis which is tantamount to using a very general model with minimal assumptions.

We have chosen to limit our considerations to the events detected in Kam-II, rather than to include those from IMB, mainly because of the larger range in arrival times, and the fact that the average energy is lower. The experiments are completely independent and significantly different, for example, their energy thresholds are different as well as their dead times (50 nsec for Kam-II, and 35 msec for IMB). To keep this analysis model independent, we avoid mixing the data from two experiments whose average event energies are very different: 16 MeV (Kam-II); 34 MeV (IMB).

The highly relativistic nature of the neutrinos allows us to express the difference in arrival times of ν_i and ν_j as

$$\Delta t_{ij} = \Delta t_{0ij} + (d/2c)(E_i^{-2} - E_j^{-2}) m_\nu^2 c^4 \ . \qquad (1)$$

In the units used here, Δt_{ij} and Δt_{0ij} are given in seconds, while the quantity $(d/2c)(E_i^{-2}-E_j^{-2})\equiv\alpha_{ij}$ is given in milliseconds, when E_i and E_j are in MeV. The quantity $x_{ij}\equiv$the magnitude of $m_\nu^2c^4$ in $(\mathrm{eV})^2$ and is dimensionless. In these units, α ranges from 0 to about 75 msec, $y_{ij}\equiv\Delta t_{ij}$ ranges from 0 to about 13 sec while $y_{0ij}\equiv\Delta t_{0ij}$ is about 1.5 sec for the collection of events used in the final analysis, as discussed later. The value of d/c adopted here is $(5.7\pm1.6)\times10^{12}$ sec quoted and used in Ref. 12. The rest mass energy is then related to x as follows: $m_\nu c^2=\sqrt{1000x}$. The errors on the quantities α_{ij} are large, but are completely accounted for in our maximum-likelihood analysis.

The first issue is that of the last three events. Figure 1 shows the plot of the frequency of y_{ij} plotted versus y_{ij}. The frequency, $N(y_{ij})$, was plotted adding one event at a time, starting with the earliest arrivals. The lowest energy event was excluded because it did not satisfy all criteria specified by the experimentors.[1] The remaining first eight ν events result in 28 values of time differences corresponding to $\alpha_{ij}>0$. They form the histogram labeled A in Fig. 1. This corresponds to $\langle y_{ij}\rangle=-0.57$ sec, with a root-mean-square deviation, $\sigma_y=1.5$ sec. As the arrival time differences involving the latest three events are included, they all fall into the histograms labeled B and C in Fig. 1. The closest value of y_{ij}, associated with cluster B, falls 4σ from the centroid of A, while that associated with C falls at about 6σ away. It is clear, that with very high probability the $\bar{\nu}$'s associated with the last three recorded events are somehow kinematically very different than those associated with the first eight. One possibility is that they are neutrinos which are unusually delayed in their escape from the core. No attempt is made to explain how the last three events were delayed, but we point out that the frequency plots, shown in Fig. 1, make a compelling case for analyzing the first eight events separately from the last three for the purpose of extracting bounds on $m_{\nu_e}c^2$. Of course, the three-piece structure of Fig. 1 is no mystery. It is a direct result of the long delay of the last three events. The histogram simply displays the effect of this delay in terms of a new parameter.

One might ask if neutrino mass could not artificially compress histogram A in Fig. 1. This is not likely because the lower-energy neutrinos observed in the detector were probably slightly delayed by cooling in the core. Higher-energy neutrinos observed in the detector were then probably emitted earlier. A nonzero neutrino mass would tend to broaden the distribution of y_{ij} rather than compress it. We will use the width of this distribution as the uncertainty in emission times in our maximum-likelihood analysis.

Figure 2 is a frequency function of $m_{\nu_e}c^2$. This was obtained by calculating x_{ij} many times, using a Monte Carlo code to select the energies E_i and E_j, in α_{ij}, according to a distribution with a width consistent to the quoted experimental errors. For the purposes of this calculation, the intrinsic width of the neutrino burst (Δt_{0ij}) was set to zero. Accordingly, this function serves only to demonstrate the effect of the large experimental errors in the neutrino energies. We estimate from the histogram in Fig. 2 that $m_{\nu_e}\lesssim 9$ eV. Later we show that inclusion of the three latest events in a maximum-likelihood analysis leads to the no clear minimization of χ^2 as a function of neutrino rest mass.

The average value $\langle x_{ij}\rangle$ and its standard deviation were also calculated in the usual way:

$$\langle x_{ij}\rangle=\sum_{i,j}(y_{ij}/\alpha_{ij})W_{ij} \tag{2}$$

and

$$\sigma_x^2=\sum_{ij}(\langle x_{ij}\rangle-x_{ij})^2W_{ij}^2 . \tag{3}$$

The inverse fractional errors in α_{ij} were used for the weighting coefficients W_{ij}. The results are $\langle x_{ij}\rangle=-0.048$, and $\sigma_x=0.157$. This corresponds to

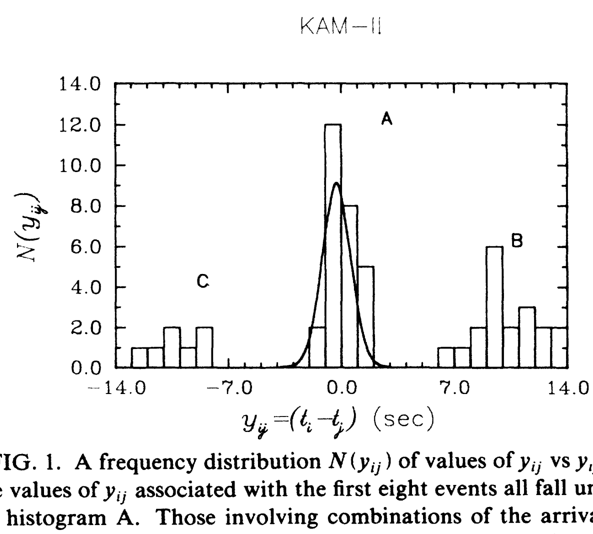

FIG. 1. A frequency distribution $N(y_{ij})$ of values of y_{ij} vs y_{ij}. The values of y_{ij} associated with the first eight events all fall under histogram A. Those involving combinations of the arrival times of the last three events are all distributed under histograms B and C. The three independent combinations of the arrival times of the last three events all fall under histogram A, but are not included in this plot.

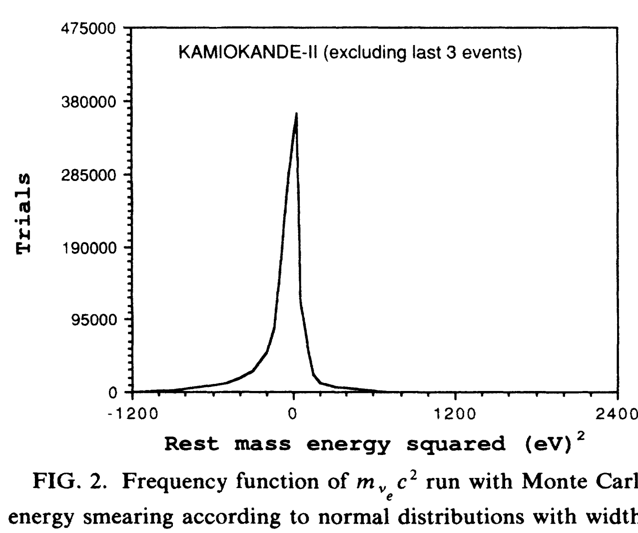

FIG. 2. Frequency function of $m_{\nu_e}c^2$ run with Monte Carlo energy smearing according to normal distributions with widths equal to the quoted experimental errors.

$m_{\nu_e}c^2 \lesssim 10$ eV, consistent with the above estimate.

Finally, a maximum-likelihood analysis that accounts for uncertainties both in α_{ij} and in y_{ij} was performed. The uncertainty in departure time was taken to be 1.5 sec consistent with the width of histogram A shown in Fig. 1. This error, and the individually computed errors in α_{ij}, were used in a likelihood function which assumes normal distributions for both y_{ij} and α_{ij}:

$$L(x)=\prod_{ij} f_{ij}(x)=e^{-\chi^2(x)/2} , \quad (4)$$

where it is straightforward to show that

$$\chi^2=\sum_{ij}(y_{ij}-x\alpha_{ij})^2(1+x^2)^{-2}(1/\sigma^2_{y_{ij}}+x^2/\sigma^2_{\alpha_{ij}}) . \quad (5)$$

The resulting χ functions are shown in Fig. 3, with and without the last three events. It is clear that these three events violently change the conclusions. Analyzing the first eight events as being kinematically distinct from the last three produces the following upper limits:

$$m_{\nu_e}c^2<9 \text{ eV } (68\% \text{ C.L.}), \quad <14 \text{ eV } (95\% \text{ C.L.}) ,$$
$$<17 \text{ eV } (99.7\% \text{ C.L.}) .$$

We conclude that the data from SN 1987A, recorded in the Kamiokande detector, is in conflict with the most recent "acceptable" range 17 eV $< m_{\nu_e}c^2 <$ 40 eV, from the Soviet tritium β-decay experiment,[19] and in serious disagreement with the best-fit value from that experiment, 30^{+2}_{-8} eV. This has also been pointed out earlier.[9,10]

A similar analysis, applied to the eight events recorded in the IMB detector, will be addressed independently.[20] It does not result in the same conclusion. In that case the distribution $N(y_{ij})$ corresponding to Fig. 1 is comprised of a single histogram, corresponding to $\sigma \cong 2.5$ sec. The likelihood function is very broad and no interesting constraints can be deduced. This very general observation should be sufficient to avoid mixing the data from the two experiments for the purpose of constraining neutrino mass.

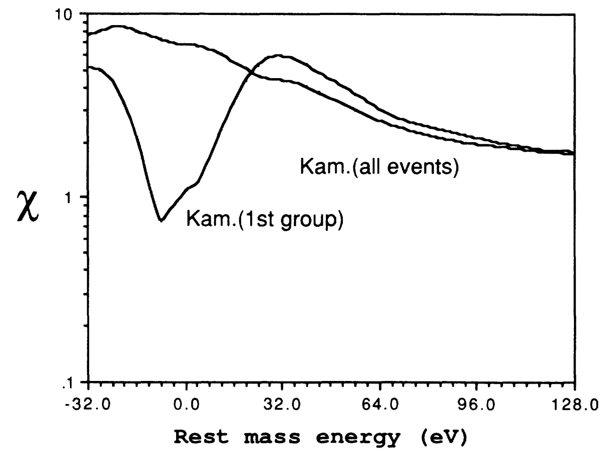

FIG. 3. Results of maximum-likelihood analysis. χ is plotted vs $m_{\nu_e}c^2$ for all time differences of the complete data set, and also for the set with the latest three events excluded from the analysis.

The arguments presented here are not completely model independent. By deriving y_{0ij} from histogram A in Fig. 1, we have assumed that this grouping is not just a statistical accident, but rather that it does reflect a time structure consistent with the emission of the majority of antineutrinos. The fact that $N(y_{ij})$ for the IMB events has only one such cluster, and no satellites, renders the statistical accident interpretation far less plausible.

We conclude that the case for considering the last three events separately, as well as that for accepting the constraints placed by these analyses, are more compelling when a detection-time difference analysis is used, rather than other model-independent analyses previously used. Our results are in excellent agreement with the model-dependent constraints of Spergel and Bahcall,[9] and those of Burrows.[10]

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