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Neutrino masses and flavors emitted in the supernova SN1987A

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The analysis of the energies and times of arrival of neutrino events in the Kamioka and Irvine-Michigan-Brookhaven detectors yields two mass groupings at ~22 eV and the other at ~4 eV, if all neutrinos were released rapidly at the supernova. A preliminary assignment of flavors to the neutrinos producing these events is attempted; this is beset with problems unless there is mixing and ν_τ are emitted more copiously than ν_e. Large statistical and systematic uncertainties necessitate caution in assessing this interpretation.

The Kamioka and Irvine-Michigan-Brookhaven (IMB) detectors recorded 12 and 8 events, respectively,[1,2] associated with the supernova SN1987A which occurred in the Large Magellanic Cloud (LMC) on February 23, 1987. It is natural to interpret the events seen in the detectors as due to neutrinos of various flavors generated copiously in the explosion. The observed spread in the arrival times could either be due to the spread in the emission times at the supernova or due to nonzero neutrino masses or both. This note discusses the implications of the latter interpretation for neutrino masses and mixing, assuming very rapid emission at the source. The arrival times with respect to the first event and the observed energies of the events are listed in Table I. The distance to the LMC is ~50 kpc and the time of flight is $t_s \approx 5\times 10^{12}$ s. The delay in arrival t of a neutrino of finite mass m is a function of its energy E_ν. The mass implied by the observed times of occurrence of the event can thus be calculated using the formula that in the relativistic limit is

$$m \approx \left[\frac{2t}{t_s}\right]^{1/2} E_\nu \, . \tag{1}$$

Noting that the neutrino energy is approximately equal to the observed electron energy, the values of m thus obtained are also listed in Table I. One notes immediately two grouping in the masses: The Kamioka events that occurred before 0.7 s have a spread in neutrino masses in the range 2.8–5.8 eV and those that occurred after 1.5 s have masses tightly clustered around 20 eV; the IMB events cluster around ~25 eV. Having noted the existence of these mass groupings, we assign initial times $t_{\text{in}}=0.1$ s for the Kamioka events and $t_{\text{in}}=0.025$ s for the IMB events. They are chosen such that when t in Eq. (1) is replaced by $t+t_{\text{in}}$ the dispersion in the masses m is minimized. This procedure affects mainly the mass groupings around 4 eV and leaves the groupings at ~20 eV essentially unchanged. The results are displayed in Fig. 1. In the same figure we also show the threshold energies E_T for the two detectors. The most probable masses corresponding to the two groups are $m_1=4$ eV and $m_2=22$ eV with mean values $\bar{m}_1=4\pm1$ eV and $\bar{m}_2=24\pm7$ eV. When propagated back to the source with these separate masses for the two groups we find that they could have been emitted within a period of about a second. On the other hand, when a single mass is used to propagate then the time spread of one group would expand and the other contract and a judicious choice should be made to minimize the spread.[3]

The threshold energies shown in Fig. 1 allow us to understand the time structure of the events: Initially the lighter of the neutrinos arrive and by $t \sim 0.1$ s all the neutrinos above the IMB threshold of 20 MeV have already gone past and are thus not seen by it. They continue to be seen by the Kamioka detector with the lower thresh-

TABLE I. The times of arrival, energies, and estimated masses shown for the Kamioka and IMB events.

No.	Time (s)	Energy (MeV)	Mass (eV)
		Kamioka	
1	0	20±2.9	
2	0.107	13.8±3.2	2.9±0.7
3	0.303	7.5±2.0	2.6±0.7
4	0.324	9.5±2.7	2.4±1.0
5	0.507	12.8±2.9	5.8±1.3
6	0.686	6.3±1.7	3.3±0.9
7	1.54	35.4±8	27.8±6.3
8	1.73	21.0±4.2	17.5±4.5
9	1.92	19.8±3.2	17.4±2.8
10	9.22	8.6±2.7	16.5±5.2
11	10.43	13.0±2.6	26.6±5.3
12	12.44	8.9±1.9	19.8±4.2
		IMB	
1	0	38±25 %	
2	0.42	37±25 %	15.2±3.8
3	0.65	40±25 %	20.4±5.1
4	1.15	35±25 %	23.7±5.9
5	1.57	29±25 %	23.0±5.7
6	2.69	37±25 %	38.4±9.6
7	5.01	20±27 %	28.3±7.1
8	5.59	24±25 %	35.9±9.0

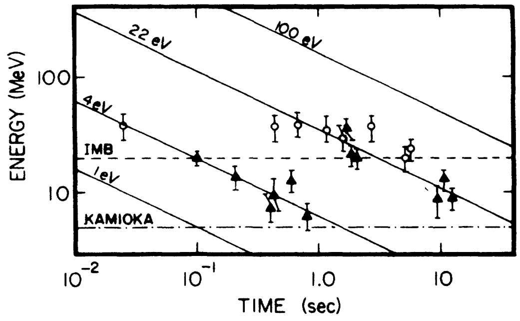

FIG. 1. The arrival time of the events is plotted against the observed energy for the Kamioka (triangles) and the IMB (circles) events. Lines of constant mass [Eq. (1)] are labeled.

old of ~6 MeV. Then by about 1 s the lowest energy that can be seen at Kamioka has already gone past. The interpretation of the arrival times of ~20 eV neutrinos is similar.

The events are projected on the mass axis in Fig. 1 and the distribution of neutrino mass implied by the events is shown in Fig. 2. Clear separation of two mass groups around 4 and 22 eV is obtained. Even though it appears natural to ascribe different flavors to the two mass groups, there are severe problems unless one takes recourse to the possibility of mixing. There are six events in each of the groups in the Kamioka detector and if one of these is due to neutrinos not of the electron type, i.e., ν_μ, ν_τ, then the scattering has to be off the electrons in the target through neutral currents. The cross sections for neutral currents are much smaller than that for charged currents on the nuclei, both because of the smaller coupling and the reduced phase space. The scattering cross section for scattering of ν_μ or ν_τ on an electron through neutral currents is given by[4]

$$\sigma_n \approx 1.4\times 10^{-45}\ (E_i/\text{MeV})\text{cm}^2\ . \qquad (2)$$

The net energy released by the supernova in neutrinos, L, required to generate n events in a detector of mass M is given by

$$L=\frac{8\pi n E_i D^2}{M A \sigma_n}\approx 10^{60}\ \text{MeV}\approx 10^{54}\ \text{ergs}\ . \qquad (3)$$

Here A is the Avogadro number and the number of electrons per gram of the detector is taken to be approximately $A/2$. Such a high amount of energy released in neutrinos is certainly untenable for a supernova. On the other hand, the charged-current cross section of $\bar{\nu}_e$ per proton is

$$\sigma_c \approx 6\times 10^{-45}\ (E_{\nu e}/\text{MeV})^2\text{cm}^2\ . \qquad (4)$$

Correspondingly the energy release needed becomes

$$L=\frac{4\pi n E_{\nu e} D^2}{M A \sigma_c \mu_p}\approx 5\times 10^{58}\ \text{MeV}\approx 8\times 10^{52}\ \text{ergs} \qquad (5)$$

for $\langle E^2_{\nu_e}\rangle^{1/2}\approx 20$ MeV and the proton mass fraction in the detector $\mu_p \approx 0.11$. This energy release is consistent with that expected on theoretical grounds.[5–8] Thus both groups of events should be assigned to charged-current events to keep the luminosity at an acceptable level.

Thus one is forced to assume mixing between neutrino states[9] where the flavor eigenstates ν_α are superpositions of the mass eigenstates ν_i. However, the level of mixing that is assumed should conform with the constraints imposed by laboratory experiments. If one assumes that there are only three flavors,[10–12] then the superposition is most conveniently analyzed in terms of the Kobayashi-Maskawa unitary matrix[13] with the Maiani parametrization[14] of the angles.[15] The Δm^2 indicated by the mass grouping is

$$\Delta m^2 \approx |m_2^2 - m_i^2| \approx 300\ \text{eV}^2\ , \qquad (6)$$

and in this region of parameter space the allowed Maiani angles are listed below:[15]

$$\begin{aligned}&\sin^2\alpha_{e\mu}<0.01,\quad \sin^2\alpha_{e\tau}<0.13\ ,\\ &\sin^2\alpha_{\mu\tau}<0.01\ .\end{aligned} \qquad (7)$$

Even though with more flavors a wider range of parametric space might be available, at present we may interpret one of the groups of events as due to $\nu_e \leftrightarrow \nu_\tau$ mixing. The ν_e and ν_τ are then to be considered superpositions of ν_1 (4 eV) and ν_2 (22 eV) with a mixing fraction corresponding to $\sin^2\alpha_{e\tau}\approx 0.1$, which is the maximum allowed by the experiment.[15] The expected number of events due to $\bar{\nu}_\tau$ is

$$n \approx MA\tfrac{1}{2}\sin^2\alpha_{e\tau}\int_{E_\tau}^{\infty} f_\tau(E)\sigma_c dE\ . \qquad (8)$$

The temperature of $\bar{\nu}_\tau$ and $\bar{\nu}_\mu$ emitted in a supernova are expected to be about a factor of 2 larger[5–8] than that for ν_e. This makes the integral in Eq. (8), which has the form $\approx T^5\int_{x_\tau}^{\infty} x^4 e^{-x}dx$, increase sensitively with temperature and thus should the effective temperature of the τ neutrinos emitted in the supernova be 2–3 times that of the e neutrinos, then one would expect comparable number of events in the two groups. From the observed energies of the events we estimate $T_{\nu e}\sim 3.5$ MeV

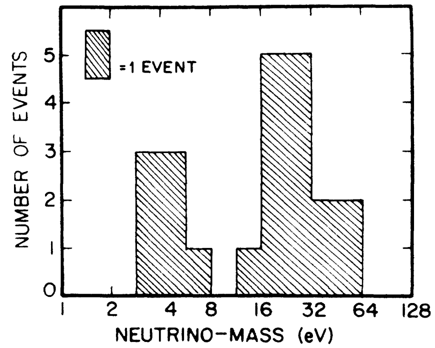

FIG. 2. The events in Fig. 1 are projected on the mass axis and the distribution obtained shows well-separated peaks at $m_1 \approx 4$ eV and $m_2 \approx 22$ eV.

and $T_{\nu\tau} \sim 8.5$ MeV, respectively. Both the uncertainties in the theoretical fluxes of the various neutrinos and the limited statistics are to be kept in mind in assessing this interpretation of the events. Since there are an equal number of events in the two groups, purely on the basis of number either group of events could be assigned predominantly to the $\bar{\nu}_\tau$ and the other to the $\bar{\nu}_e$. If one believes in the hierarchy of masses, then the second group with mass ≈ 22 eV should be caused by antineutrinos which are predominantly τ. There are as yet no compelling reasons supporting the hierarchical mass spectrum, of course. Assuming ν_μ to have the same spectrum as ν_τ, the net luminosity in neutrinos of all flavors turn out to be 8×10^{53} ergs.

The importance of such neutrino masses in cosmology essentially stems from the fact that in a hot big-bang Universe the present number density of neutrinos of each flavor is $\sim 55\ \mathrm{cm}^{-3}$, far in excess of the mean number density of nucleons of $\sim 10^{-7}\ \mathrm{cm}^{-3}$; the implications of a finite mass for the neutrinos have been discussed extensively in literature.[16-24] Even neutrinos of a single flavor having a mass of ~ 22 eV will yield an average energy density in the Universe of $\rho_\nu \approx 2.4\ \mathrm{keV\ cm}^{-3}$, since their number density today is $n_\nu = n_{\bar{\nu}} = 55\ \mathrm{cm}^{-3}$. For a Hubble constant, $H_0 = 55\ \mathrm{km\,s^{-1}Mpc^{-1}}$, the critical density[22,23] $\rho_c \approx 3.5\ \mathrm{keV\,cm}^{-3}$, and the density of visible matter in baryons is $\rho_B \approx 0.1\ \mathrm{keV\,cm}^{-3}$. Thus the neutrino masses implied by Kamioka and IMB results make them gravitationally the dominant constituents of the Universe.

In conclusion, then, the events observed at Kamioka are interpreted as due to neutrinos from the supernova. The arrival time of the events when analyzed in association with their individual energies indicate masses $m_{\nu 1} \approx 4$ eV and $m_{\nu 2} \approx 22$ eV. The relative number of events in the two groups can be understood if ν_τ and ν_e are superpositions of these mass states with a Maiani angle $\sin^2\alpha_{e\tau} \approx 0.1$. The neutrino with $m_{\nu 2} = 22$ eV alone would yield $\Omega \approx 0.7(55/H_0)^2$ and along with $m_{\nu 1} \approx 4$ eV this increases to $\Omega \approx 0.75(55/H_0)^2$, thus bringing the neutrino densities to close agreement with other determinations of the mass density of the Universe.[25] Keeping in mind these important implications, it is advisable to exercise caution in assessing this interpretation of the neutrino data which have rather large systematic and statistical uncertainties.

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[1] R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[2] K. Hirata *et al.* Phys. Rev. Lett. **58**, 1490 (1987).

[3] E. W. Kolb, A. J. Stebbins, and M. S. Turner, Phys. Rev. D **35**, 3590 (1987), and references therein, in particular J. Bahcall and S. L. Glashow, Nature (London) **326**, 476 (1987); A. Burrows and J. M. Lattimer, Astrophys. J. Lett. **318**, L63 (1987).

[4] E. D. Commins and P. H. Bucksbaum, *Weak Interactions of Leptons and Quarks* (Cambridge University Press, Cambridge, England, 1983); Particle Data Group, R. L. Kelly *et al.*, Rev. Mod. Phys. **52**, S1 (1980); J. N. Bahcall, Rev. Mod. Phys. **50**, 881 (1978).

[5] J. R. Wilson, Phys. Rev. Lett. **32**, 259 (1974).

[6] D. Z. Freedman, D. N. Schramm, and D. L. Tubbs, Annu. Rev. Nucl. Sci. **27**, 167 (1977).

[7] W. D. Arnett, Astrophys. J. Lett. **263**, L55 (1983); S. W. Bruenn, Astrophys. J. Suppl. Ser. **58**, 771 (1985).

[8] D. N. Schramm, J. R. Wilson, and R. Mayle, Nuovo Cimento **9C**, 443 (1986).

[9] S. M. Bilenky and B. Pontecorvo, Phys. Rep. **41C**, 225 (1978); A. De Rújula *et al.* Nucl. Phys. **B168**, 54 (1980).

[10] J. Yang, M. Turner, G. Steigman, D. Schramm, and K. Olive, Astrophys. J. **281**, 193 (1984).

[11] A. M. Boesgaard and G. Steigman, Annu. Rev. Astron. Astrophys. **23**, 319 (1985).

[12] J. Ellis, D. V. Nanopoulos, and S. Sarkar, Nucl. Phys. **B259**, 175 (1985).

[13] M. Kobayahsi and K. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[14] L. Maiani, in *Proceedings of the International Symposium on Leptons and Photon Interactions at High Energies*, edited by F. Gutbrod (DESY, Hamburg, 1977), p. 877.

[15] H. Blumer and K. Kleinknecht, Phys. Lett. **161B**, 407 (1985).

[16] S. S. Gerstein and Ya B. Zeldovich, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 156 (1966) [JETP Lett. **4**, 1107 (1966)].

[17] R. Cowsik and J. McClelland, Phys. Rev. Lett. **29**, 669 (1973).

[18] R. Cowsik and J. McClelland, Astrophys. J. **180**, 7 (1973).

[19] G. Marx and A. S. Szalay, Astron. Astrophys. **49**, 437 (1976).

[20] J. R. Bond, G. Efstathiu, and J. Silk, Phys. Rev. Lett. **45**, 1980 (1980).

[21] H. Sato and F. Takahara, Prog. Theor. Phys. **64**, 2029 (1980).

[22] R. Cowsik and P. Ghosh, Astrophys. J. **317**, 26 (1987).

[23] J. Bernstein and G. Feinberg, Phys. Lett. **101B**, 39 (1981).

[24] R. Cowsik, Phys. Lett. **151B**, 62 (1985).

[25] E. D. Loh, Phys. Rev. Lett. **57**, 2865 (1986).