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On the delayed low-energy events in the neutrino-burst data from SN 1987A

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An attempt has been made to attribute the delayed low-energy events in the neutrino-burst data from SN 1987A obtained by the Kamiokande-II and the Irvine-Michigan-Brookhaven Collaborations to a few energy-dependent effects on the propagation of the neutrinos. While attribution of the events to the neutrino-mass effect provides no attractive information on the mass, analysis of the data with a novel energy dependence of the velocity of massless particles due to an unknown elementary length l_0 in space yields an interesting result: the observed time-energy profiles of the burst are roughly explained when one assumes $l_0 \sim 1\times 10^{-18}$ cm and the related increases of $\sim 1/10^{13}$ and $\sim 1/10^{12}$ in velocities of massless particles of energies 10 and 30 MeV, respectively. This assumption appears not to be rejected by any existing experimental data. Precision velocity measurements at higher energies are desirable for checking this possibility.

It is well known that the neutrino-burst events from SN 1987A recently detected by the Kamiokande-II[1,2] (KII) and the Irvine-Michigan-Brookhaven[3,4] (IMB) Collaborations have proved for the first time the validity of the outline of the current theory on stellar core collapse of type-II supernovas. As for the details of the observations, however, there seem to be some problems yet left beyond our complete understanding.

One of those problems is the physical meaning of the low-energy events observed in each detector with a substantial delay (~ 9 sec in KII; ~ 5 sec in IMB). While the observed number of such delayed events is only two (IMB) or three (KII), the weight of those events could become comparable to that of the preceding higher-energy events if energy dependence of trigger efficiency of the detector and that of cross sections for neutrino reactions are taken into account. According to the standard scenario of stellar core collapse of type-II supernovas,[5] the width of the burst peak in the time-versus-neutrino-luminosity curve is in typical cases less than about 0.5 sec, and the luminosity becomes more than an order of magnitude lower than the peak value when one goes to the tail of the curve. Attention should therefore be directed to the reason for the occurrence of those delayed low-energy events.

It might be possible to construct an improved scenario of the core collapse in SN 1987A in which such delayed low-energy events are reasonably explained in terms of cooling of this newborn neutron star,[6] increasing gravitational red-shift,[6] and/or possible accretion of the collapsed core which might have occurred continuously for several seconds following its collapse.[7] There appears, however, not yet to be any numerical computation which explains in a convincing manner the time-energy profiles of the burst observed by KII and IMB. In view of these circumstances, it would be of meaning to investigate the observed too-long duration of the burst from some different angles.

The purpose of this paper is thus to try to interpret the delayed low-energy events with some conceivable effects on the propagation of the neutrinos. We should first notice that, in the said observations of the neutrino-burst events, the neutrinos have been detected indirectly via the electrons emitted in some reactions caused by themselves in the water pools. In searching for an energy-dependent effect on the burst profiles, therefore, it is important that we can be convinced, for every event, of the near equality of the observed electron energy to that of the arriving neutrino. For neutrinos of energies 10–20 MeV, inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) is dominant in water,[2,8,9] and therefore the observed electron energy is unambiguously regarded as equal to the energy of the neutrino apart from a small energy loss of less than about 10%. On the other hand, for neutrinos of energies about 35 MeV, for instance, contributions from the reactions $\nu_e + \mathrm{O} \rightarrow e^- + \mathrm{F}$ and $\bar{\nu}_e + \mathrm{O} \rightarrow e^+ + \mathrm{N}$ become much more important.[8,9] The total cross section (multiplied by the number density of the target) for each of these reactions amounts to about one-third of that for inverse beta decay;[9] that is to say, about 40% of the reactions caused by 35-MeV neutrinos in water should be regarded as ν_e-O or $\bar{\nu}_e$-O (Ref. 10). In these nuclear reactions, more than 10–15 MeV of the neutrino energy is transferred to the nucleus,[8] and the electron is ejected with the remaining half of the neutrino energy. Because of the high threshold energy in the electron detection (~ 20 MeV), the IMB detector is considered to be almost insensitive to such a low-energy electron. Thus we may safely assume that every burst event detected by IMB is due to the $\bar{\nu}_e$-p reaction and hence the observed electron energy is close to the energy of the arriving neutrino.

In view of the above argument, the said examination of the burst profiles in this work will be performed in the following two steps. First, a preliminary analysis will be made on the IMB data only. If once an attractive result is found, then the result will be tested to see what modification is required of it when the KII data are also included in the analysis.

The first propagation effect to be discussed here is that of neutrino mass.[11] Let m_ν denote the mass and L

denote the distance to SN 1987A ($\sim$55 kpc) (Ref. 12). Then the delay in the arrival time of a neutrino of energy E is given in the form

$$\Delta t_1 = +(L/2c)(m_\nu c^2/E)^2 \ . \tag{1}$$

Note that this delay is inversely proportional to E^2.

Figure 1(a) shows a result of fitting of Eq. (1) to the new IMB data (open circles) (Ref. 4). The best fit is obtained with $m_\nu = 34$ eV/c^2 as shown by the solid line. The dashed lines in the figure define a possible area for the burst profile to be expected when it is tentatively assumed that the emission of neutrinos from SN 1987A continued for 3 sec. Similar fittings with m_ν as a parameter set a range 34^{+10}_{-5} eV/c^2 (significant at the 95%-confidence level) of the neutrino mass. This lower limit is a little too high as compared with some of the upper limits set by several laboratory experiments on tritium beta decay : $17 < m_\nu < 40$ eV/c^2 (Moscow) (Ref. 13), $m_\nu < 27$ eV/c^2 (Los Alamos) (Ref. 14), $m_\nu < 18$ eV/c^2 (Zürich) (Ref. 15), $m_\nu < 32$ eV/c^2 (Tokyo) (Ref. 16), and $m_\nu < 28$ eV/c^2 (Tokyo) (Ref. 17). Since, as seen in the above, the result of the analysis of the IMB data does not appear to be attractive, we shall not discuss the mass effect further in this work.

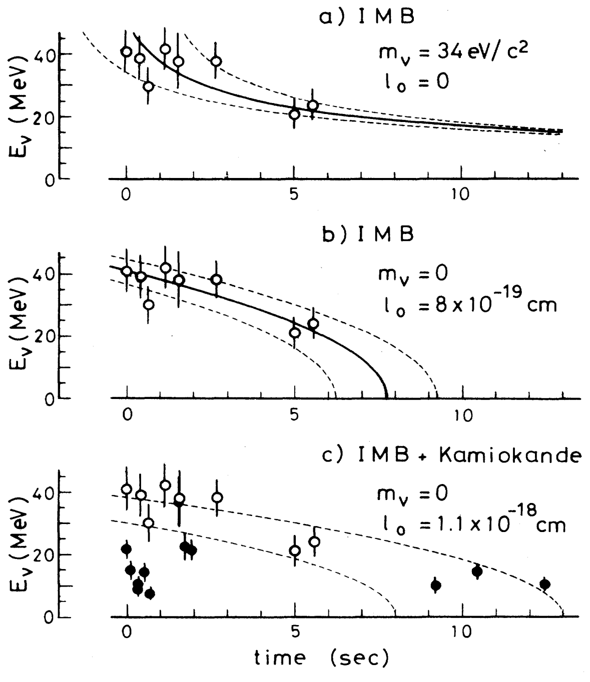

FIG. 1. Fitting of Eq. (1) (possible mass effect) or Eq. (3) (possible elementary-length effect) to the neutrino-burst data from SN 1987A (closed circles for Kamiokande; open circles for IMB). In plotting the experimental data, it has been tentatively assumed that all the events were detected via inverse beta decay, and hence the observed electron energies are close to those of the arriving neutrinos. This assumption could be inappropriate to some of the several earliest Kamiokande events, while it would be appropriate to the IMB ones. The detailed discussion is found in the text.

The neutrino burst in SN 1987A is the only known phenomenon which affords us today an opportunity to test the propagation of particles of different energies leaving the same source almost at the same time and arriving at the same detector after having traveled an astronomical distance. It might be indicating some new effect too fine to have so far been noticed on Earth. The observed spread in the arrival times of the neutrinos should therefore be examined carefully but free from any constraint of today's common sense. The second effect on the neutrino propagation which we wish to discuss here is the possible increase in the velocity of photons and other massless particles with the increasing energy.[18] In truth, such a possibility will improve short-distance behavior of the propagators of all the particles effectively and make the field theories finite. This was first pointed out by Pavlopoulos[19] and later formulated independently by the present author[20] into a much more elaborate, logically consistent method for finitizing field theories without changing their conventional form. In a recent work,[21] a finitized form of the Coulomb potential and an improved short-distance behavior of the quantum-electrodynamic coupling constant have been derived as typical examples of the finitization.

In this theory,[20] existence of a pure-imaginary elementary length $2il_0$ is assumed in the three-dimensional space, where l_0 is the possible third natural constant to be searched for. On this assumption, velocity of a massless particle of energy E is modified to[20]

$$C(E) = c\cosh[\operatorname{arcsinh}(l_0E/\hbar c)]$$

$$\simeq c[1+\tfrac{1}{2}(l_0E/\hbar c)^2] \quad \text{for } E \ll \hbar c/l_0 \ . \tag{2}$$

If neutrinos are assumed to be massless, then the resultant shortening in the time of flight (between SN 1987A and Earth) of a neutrino of energy E is written in the form

$$\Delta t_2 = -(L/2c)(l_0E/\hbar c)^2 \ . \tag{3}$$

Notice that Δt_2 is proportional to E^2 just contrary to Eq. (1).

Figure 1(b) shows a typical result of fitting of Eq. (3) to the new IMB data.[4] The best fit between them is obtained with $l_0 = 8\times10^{-19}$ cm as shown by the solid line. When 3-sec duration of the neutrino emission is tentatively assumed (thin broken lines), all the events fall in the predicted area within their possible experimental errors. Similar fittings with l_0 as a parameter set a definite lower limit $l_0 > 6\times10^{-19}$ cm on this parameter, while the upper limit is found to be larger than 3×10^{-18} cm. A more stringent upper limit on l_0 will be placed by an existing terrestrial experiment[22] as mentioned later.

Our next task is to try to explain both KII and IMB data with a unified model. Such an attempt faces inevitably a few insoluble problems arising from the 1-min uncertainty in the absolute timing of the KII events or from marked differences in the detector characteristics between the two. Nevertheless, in Fig. 1(c), the KII[2] (closed circles) and IMB[4] (open circles) events are plotted in a common diagram on the tentative assumptions that the detections of the burst events by the two detectors started almost at the same time, and that all the neutrinos were detected via $\bar{\nu}_e$-p reactions. Possible inappropriateness of the latter assumption to the KII data will be discussed shortly. The dashed curves in the figure show, as an example, the time-analyzed burst spectrum to be expected from Eq. (3) when $l_0 = 1.1 \times 10^{-18}$ cm and 5-sec source duration are assumed. The majority of the events appear to be well explained with this model within the possible experimental errors. According to this model, however, only neutrinos of energy around 35 MeV should hit the detectors in the period of the earliest few seconds. This requirement is clearly incompatible with the first six events at KII, while it is supported to a certain extent by the nonobservation of neutrinos of energy less than 30 MeV at IMB in the same period. The poor fitting to those earliest events in the KII burst profile, however, does not necessarily mean that our l_0-effect model is to be rejected by those events, because there remains a non-negligible possibility of their being due to reactions other than $\bar{\nu}_e$-p, and hence being much higher in the incident neutrino energies.

The first KII event [$E_e = 20.0 \pm 2.9$ MeV, $\theta = 18° \pm 18°$ (Refs. 1 and 2) or $10° \pm 18°$ (Ref. 2)] is likely to be ν_e-e^- scattering of an electron neutrino emitted in the initial neutronization burst (see the remarkably high, narrow peak on the time-versus-ν_e-luminosity curve shown in Ref. 5.) as suggested by the KII authors themselves.[1,2] According to weak-current calculation on ν_e-e^- scattering,[23] half of the colliding neutrinos are, in the case of 35-MeV ν_e incidence, for instance, scattered into angles $5.5°^{+5}_{-3}$ from the incidence direction, and at the same time the electrons are recoiled with the recoil angles $17°^{-8}_{+19}$. In such a scattering, fraction of the incident energy transferred from the neutrino to the electron is not so high; it is only about a half when the recoil angle is about 10°, for instance, thus explaining the lowness in energy of the first event.

The sixth KII event ($E_e = 6.3 \pm 1.7$ MeV) is of very low energy, and hence might be a noise as implicitly suspected by the KII authors in their earliest report.[1] (Notice that the background trigger rate of the KII detector is, on average, 0.60 sec of which 0.23 sec is due to radioactive contaminations in the water.[1,2])

As for the second KII event, two very different values, $15° \pm 27°$ (Refs. 1 and 2) and $40° \pm 27°$ (Ref. 2), depending on the vertex-reconstruction program have been reported for the angle of the electron. If the former should be accepted, there would arise a possibility that this event, too, may be a ν_e-e^- scattering. In the following, however, we shall discuss only the possibility that the four KII events from the second to the fifth may be due to ν_e-O or $\bar{\nu}_e$-O. As mentioned in the introductory part of the present article, about 40% of the reactions caused by 35-MeV neutrinos in water should be regarded as ν_e-O or $\bar{\nu}_e$-O. Therefore, if those four events are assumed to be due to neutrinos of energy about 35 MeV, then it is found most probable that two of the four events are ν_e-O or $\bar{\nu}_e$-O, thus improving the fitting considerably. The probability that all the four events are ν_e-O or $\bar{\nu}_e$-O is, on the other hand, given by $(0.4)^4$. This value is not high, but still to be considered as non-negligible. Thus we understand that our l_0-effect model can hardly be rejected by the KII data.

There are a few velocity measurements[22,24] at about 10 GeV. Guiragossian *et al.*[22] compared the velocity of 14-GeV photons with that of electrons being continuously accelerated from 15 to 20.5 GeV, and obtained the relative velocity difference $(1.25 \pm 1.91) \times 10^{-7}$ or $(-5.36 \pm 5.75) \times 10^{-7}$ according to whether or not about 40% of the data had been omitted as being anomalous. Their results imply that $l_0 \lesssim (1.1\text{–}2.0) \times 10^{-18}$ cm. Then, combining it with our lower limit, we find that

$$6 \times 10^{-19}\ \text{cm} < l_0 \lesssim (1.1\text{–}2.0) \times 10^{-18}\ \text{cm} \qquad (4)$$

as long as the above-mentioned dispersion due to l_0 really is the case.

If l_0 could be about 1×10^{-18} cm, then the relative increase in photon velocity would be 1×10^{-5} at 100 GeV and 1×10^{-3} at 1 TeV. A precision velocity measurement is desirable in the energy range of 10^2–10^3 GeV for checking this possibility. Such a measurement would not lose its importance even when it results in a negative conclusion, because the negative result would then mean that the validity of one of the most fundamental postulates in today's physics (i.e., the energy independence of photon velocity or, in other words, the continuity of the space) would have been verified for the first time up to 10^2–10^3 GeV.

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[21] K. Fujiwara (unpublished). In this work, it has been shown that (1) the Coulomb potential due to a point charge q takes a finite value $q/12\epsilon_0 l_0$ at the origin, and (2) the QED coupling constant effective at a large three-momentum transfer $\mathbf{Q}$ is given in the finite form $\alpha(\mathbf{Q}^2)\sim\alpha_0/[1-A\alpha_0(M^2/\mathbf{Q}^2)^{5/4}]$, where α_0 is the coupling constant for the bare electronic charge, A is a positive coefficient, and $M=1/2l_0$ is a large momentum which corresponds to the cutoff momentum in the renormalization theory.

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