Characteristics of the neutrino emission from supernova SN1987A

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The total energy released in electron antineutrinos and the temperature and radius of the neutrinosphere of supernova SN1987A are estimated on the basis of data from four experimental installations which detected neutrino emission upon the collapse of the star. Only the data from the Kamiokande installation conform to the present theoretical understanding.

The idea of detecting a neutrino burst from the gravitational collapse of a star was raised[1] in 1965. In 1977 a program to carry out an experimental search for this effect was discussed and undertaken. Four experimental groups[3–6] recently reported the possible observation of a neutrino burst associated with a supernova in the Large Magellanic Cloud on 23 February 1987. One of the groups (working with the LSD detector in a tunnel under Mt. Blanc) detected five pulses over the course of 7 s, beginning at 2 h 52 min 36.792 s. At that time the three other installations observed nothing in the way of a significant signal rising above the background level. Between 7 h 34 min and 7 h 37 min, the IMB detector, the Kamiokande detector, and the Baksan underground telescope detected 8, 12, and 3 pulses, respectively (for the latter installation, only the inner layers were taken into consideration). The events at the IMB and Baksan installations could not have been caused by the same neutrino burst, since they were detected at times ~25 s apart. The time at which the event was detected at the Kamiokande installation is known only within a rather large uncertainty ~1 min. Consequently, there is no mutually independent and rigorously simultaneous observation of a neutrino signal at the different installations. Despite this unfortunate circumstance, the experimental data can be used to estimate some general characteristics of the emitting object: the total energy release in electron antineutrinos and the temperature and radius of the neutrinosphere. These estimates can be used in turn to compare the results obtained at the various installations with each other and with the standard theory.[7]

The distribution of the number of pulses observed by an installation in the antineutrino energy E_ν (MeV) can be written

$$dN = f(E_\nu, T)dE_\nu = C\frac{E_\nu^2}{1+\exp(E_\nu/T)}\exp\left(-\alpha\left(\frac{E_\nu}{T}\right)^2\right)\Phi_{\text{tanh}}(E_\nu)(E_\nu - 1.29\,\text{MeV})^2\,dE_\nu, \tag{1}$$

where T is the maximum brightness temperature of the neutrinosphere; the second and third factors are the neutrino spectrum in the standard theory[5]; $\Phi_{\text{th}}(E_\nu)$ is the detection efficiency, which is a function chosen empirically to allow for the energy thresh-

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old of each installation; and the last factor is proportional to the cross section for the interaction of electron antineutrinos with free protons of the target.

If the constant C is chosen for each temperature T in such a way that the condition

$$\int f(E_\nu, T)dE_\nu = 1$$

holds, the likelihood function will be

$$L(T) = \prod_{i=1}^{m} f(E_{\nu_i}, T),$$

where m is the number of pulses detected, and E_{ν_i} is the energy of the antineutrino which caused the given pulse. The energy of the antineutrino is assumed to be equal to the energy evolved in the energy detector plus 0.8 MeV for the scintillation detectors and 2.05 MeV for the Čerenkov detectors. In this way we allow for the difference between the positron detection efficiencies of the scintillation and Čerenkov detectors. For the Baksan underground telescope, we considered only the three pulses detected in the inner layers of the telescope; the mass of the target would then be 130 metric tons of scintillator.

Figure 1 shows normalized functions $L(T)$ calculated for the parameter value $\alpha = 0.04$. The relative positions of the curves in Fig. 1 remain essentially the same, even when the parameter α is varied dramatically. At $\alpha = 0$, for example, all the temperatures decrease by a factor of about 1.5. Furthermore, essentially no substantial changes occur when the one or two pulses with the lowest energy are discarded.

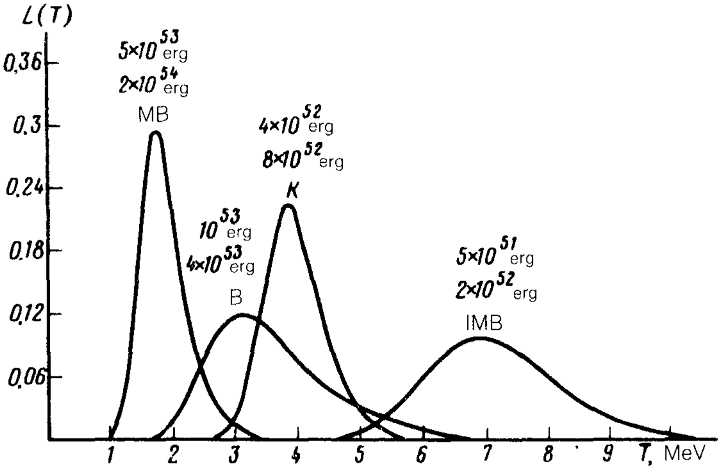

FIG. 1. Likelihood function for the events detected by various detectors, if these events were caused by the neutrino burst accompanying the collapse of a star. MB—LSD; B—Baksan underground telescope; K—Kamiokande; IMB—IMB.

The standard theory predicts a value of 3–5 MeV for the temperature of the neutrinosphere; only the events detected by the Kamiokande and Baksan installations fall in this range. The probability that the Kamiokande and IMB events were caused by the same neutrino burst, with $T = 5$ MeV, is small ($< 10^{-2}$).

Knowing the number (N_p) of free protons in the installation, the cross section for the interaction of antineutrinos with free protons, the distance to the object (R), the energy and number of observed pulses, and the detection efficiency, we can calculate $Q_{\tilde\nu_e}$, i.e., the total energy of all the electron antineutrinos emitted by the star:

$$Q_{\tilde\nu_e} = A\frac{4\pi R^2}{N_p}\sum\frac{E_{\nu_i}}{\sigma_0(E_{\nu_i}-1.29)^2}\,.$$

The coefficient $A > 1$ reflects the fact that in an actual experiment the neutrino detection efficiency depends on the energy and is given as the ratio of two integrals:

$$A = \int E_\nu\frac{E_\nu^2}{1+\exp(E_\nu/T)}\exp\left(-\alpha\left(\frac{E_\nu}{T}\right)^2\right)dE_\nu \Big/ \int E_\nu\frac{E_\nu^2}{1+\exp(E_\nu/T)} \times \exp\left(-\alpha\left(\frac{E_\nu}{T}\right)^2\right)\Phi_{\tanh}(E_\nu)dE_\nu\,.$$

Figure 2 shows the corresponding curves of $Q_{\tilde\nu_e}$ versus the temperature for all four installations. The horizontal dashed line is the energy release which would be expected in the standard theory; roughly speaking, it is equal to the gravitational energy of the star divided by the number of neutrino species. We see that only the signals detected at the Kamiokande and IMB installations yield an energy release corresponding to the theoretical value. The signal detected at the Baksan underground telescope is close to this value, but it is four times the value found by the Kamiokande detector.

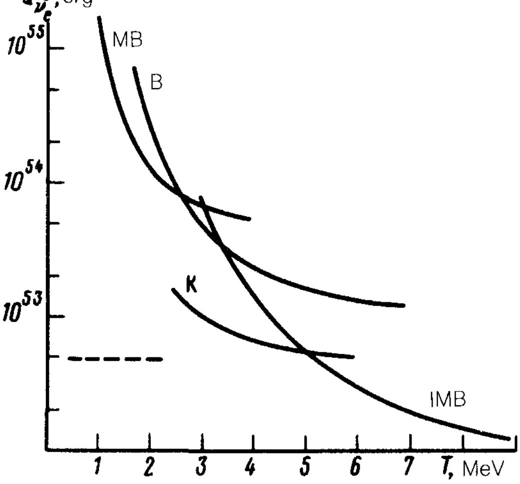

FIG. 2. The total energy release in electron antineutrinos which would be required to produce the signals observed by various detectors, as a function of the temperature.

The data from the LSD installation[5] yield an energy release and a temperature which are totally at odds with the present theoretical understanding. Furthermore, such parameter values lead to an excessively large radius for the emitting object. Working from the Stefan-Boltzmann law which relates the luminosity, the temperature, and the surface area of an emitting object, we find the radius of the emitting sphere to be

$$r \geqslant 420\ \mathrm{km} \left(\frac{Q_{\tilde{\nu}_e}\ (\mathrm{erg})}{10^{52}} \right)^{1/2} \left(\frac{7}{16} \sigma t \right)^{-1/2} T^{-2}\ (\mathrm{MeV}) = 650\ \mathrm{km}.$$

If we take the mass density below the neutrinosphere to be 10^{13}–10^{14} g/cm^3 in accordance with the theory, we find a mass on the order of $10^5 M_\odot$; if we assume a mass on the order of $10 M_\odot$, we find a density of 10^{10} g/cm^3. Such a density would be possible before the collapse, but not during it. The signal detected at the LSD installation thus cannot be described by the standard theory; it requires invoking some new—presently unknown—mechanisms for neutrino production. In addition, we see a contradiction between the data from the LSD and Kamiokande detectors in terms of the number of detected pulses. If we assume a Planck spectrum and work from the data obtained by the LSD detector, we conclude that we should find 30–50 pulses at the Kamiokande detector, depending on the temperature and the parameter. In fact, no more than four were observed. It would be possible to reconcile the results if the high-energy cutoff of the neutrino spectrum were sharper than follows from the present theory.

If we take the parameters of the neutrino burst which follow from the Kamiokande data as the most probable, and if we set $T = 4$ MeV and $\alpha = 0.04$ ($\alpha = 0$), we would expect to find 0.1 (0.5) of a pulse at the IMB installation, instead of the eight detected, while at the Baksan underground telescope we would expect to find 0.7 (1) in comparison with the three observed. Again in this case it would be possible to reconcile the data from the Kamiokande and IMB detectors within the framework of the standard theory, specifically, by using a neutrino spectrum with a high-energy tail.

In summary, the reliability of the detection of a neutrino burst from the gravitational collapse of a star is not a simple and unambiguous matter which requires, in our view, a further and more-detailed study: both an examination of other theoretical possibilities and a reexamination of the experimental data. For example, if it were possible to alter the energies of the events at the Kamiokande and IMB detectors on the basis of uncertainties of some sort in the absolute calibration (the energies of the events at the Kamiokande detector would have to be increased, and those at the IMB detector reduced by 20%), then it would become possible to reconcile the data from these two detectors at a temperature of 5 MeV and a total energy release of 5×10^{52} erg. Whether such manipulations are possible, however, is totally in the hands of the corresponding experimentalists.

As the manuscript for this letter was being prepared, several preprints appeared[8–10] with an analysis similar to our own. However, after finding approximately the same parameter values as we did, Burrows and Lattimer,[8] De Rujula,[9] and Spergel *et al.*[10] reached the diametrically opposite conclusion that the experimental data are completely in agreement with each other and also with the standard theory. We would like to stress again that, in our view, the only data which agree with the generally accepted theory are the data obtained by the Kamiokande group; in the other cases, there are discrepancies which go beyond the possible statistical errors.

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