Resonant oscillations and limitations found on neutrino parameter values from the possible observation of a ν burst from the gravitational collapse of a star

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Limitations on neutrino parameter values are found from the possible observation of a neutrino signal associated with the supernova SN1987A. Resonant oscillations are taken into account. The effect of the material of the earth is estimated.

The detection of a ν burst from the gravitational collapse of a star[1–4] provides unique information on the properties of neutrinos, including a limitation on the decay time,[3] $\tau(\nu_e) > 10^5$ yr, and a limitation on the mass, from the temporal smearing of the ν pulse.[5] From the observed energy spread of events and from the observed length of the ν pulse we find $m(\nu_e) < 10$–15 eV.

1. Over broad ranges of $\Delta m^2 = m_1^2 - m_2^2$ and of $\sin^2\theta$, where θ is the neutrino mixing angle, the resonant oscillations in a collapsing star substantially change the properties of the ν fluxes.[6] The effects are determined by the density profile along the path of the neutrinos, $\rho(r)$. The profile $\rho(r)$ changes over the duration (≈ 10 s) of a ν burst. Here are the most important limiting $\rho(r)$ configurations which could correspond to the supernova SN1987A (Ref. 7).

A. Presupernova. Its core has a length scale $R_B = (1$–$3) \times 10^{10}$ cm and a central density $\rho_c \cong (1$–$3) \times 10^9$ g/cm^3. The density profile at $\rho \ll \rho_c$ is approximated by $\rho = \rho_0(R_B/r - 1)^3$.

B. After the collapse of the central regions of the core, the onset of a neutrino opacity, and the fall of the outer layers ($\Delta t = 0.1$–1 s), a more compact object forms, with $R = (3$–$10) \times 10^8$ cm and a density $R_\nu = (1$–$7) \times 10^{13}$ g/cm^3 in the neutrino-

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sphere. The object may be surrounded by a shell which is a source of nuclear burning with $R \simeq 10^{10}$ cm.

C. By the end of the neutrino pulse, a neutron star with $R_N \simeq 10$–30 km (or a black hole) forms, as does an expanding envelope, which occupies a volume with $R_0 = (1\text{–}3) \times 10^{10}$ cm. Most of the ν flux is emitted in stages B and C.

The oscillatory suppression of luminosity in neutrinos, $\bar{\nu}_e\, (\nu_e) L_{\bar{\nu}}(t)$, is described by the factor

$$R(\Delta m^2, \sin^2 2\theta, t) = L_0^{-1} \int_0^{\infty} dE\, E \sum_{\alpha} F_{\alpha}^{0} (E, t)\;\; P_{\alpha \to e} \left(\frac{E}{\Delta m^2}, \sin^2 2\theta, t \right), \qquad (1)$$

where $L_0 = \int dE E F_e(E)$, $P_{\alpha \to e}$ is the probability for the oscillatory transition $\nu_\alpha \to \nu_e$, and F_α^0 is the flux of neutrinos of type α without allowance for oscillations. For profiles A and B, we calculated $P_{\alpha \to e}(E/\Delta m^2, \sin^2 2\theta)$ and used the results to find contour lines of the suppression of the energy of the ν burst: $R(\Delta m^2, \sin^2 2\theta) = a = \text{const}$ (Figs. 1 and 2). [As $F_\alpha^0(E)$ we used Planckian spectra with a high-energy cutoff and various values of T.] In evaluating the suppression of the ν peak due to neutronization we used profile A, the one term $F_e^0 P_{e-e}$ in (1), and $\bar{E}_\nu = 15$ MeV (Fig. 1). In the stage of ν opacity (B–C), comparable fluxes of ν_e and ν_μ (ν_τ) are emitted: $F(\nu_\mu) \simeq F(\nu_e)/2$, $\bar{E}(\nu_\mu) \simeq 2\bar{E}(\nu_e) \simeq 30$ MeV, and $L(\nu_\mu) \simeq L(\nu_e)$. The exchange of the ν_e and ν_μ spectra due to ν_e–ν_μ oscillations thus does not change the total energy $\mathscr{E}(\bar{\nu}_e) = \int dt\, L_\nu(t)$ and $R \simeq 1$, but the number of events at a detector will increase because of the energy dependence of the cross section, $\sigma \sim E^2$. The dimension R is different from unity at the edges of the resonant range, where the exchange of the ν_e and ν_μ spectra is not symmetric: At the upper edge (in Δm^2), the ν_μ go into a region of an intense transition, and the ν_μ convert into ν_e to a greater extent than the ν_e convert into ν_μ, so we have $R(\nu_e) > 1$. At the lower edge we have the opposite situation and $R(\nu_e) < 1$ (Fig. 1).

The structure of the lines of equal suppression for oscillations into sterile states, $\bar{\nu}_e - \bar{\nu}_s$ (Fig. 2), results from the circumstance that the effective density (which determines the effect of matter) changes sign in the region of strong neutronization: $\rho^{\text{eff}} = \rho(Y_p - Y_n/2)$, where Y_p and Y_n are the fractions of protons and neutrons per nucleon.[6] In the central part of a star, with $Y_n > 2Y_p$, the resonant condition holds for $\Delta m^2 < 0$, while in the outer regions it holds for $\Delta m^2 > 0$.

The shape of the lines of $R(\Delta m^2, \sin^2 2\theta) = a$ is determined by the maximum densities in the star and by the condition for a deviation from an adiabatic situation, which depends on ρ; specifically, it is proportional to $d(\ln \rho)/dr$. With $\Delta m^2 = 10^4$–10^8 eV^2 we would have to allow for the averaging due to inelastic collisions of neutrinos. It would seem that variations in the model of the star could change the positions of the lines by no more than an order of magnitude.

2. The fact that a neutrino burst is detected leads to severe limitations on Δm^2 and $\sin^2 2\theta$. The experimentally permissible suppression of the energy in $\overset{(-)}{\nu}_e$ can be estimated in several independent ways:

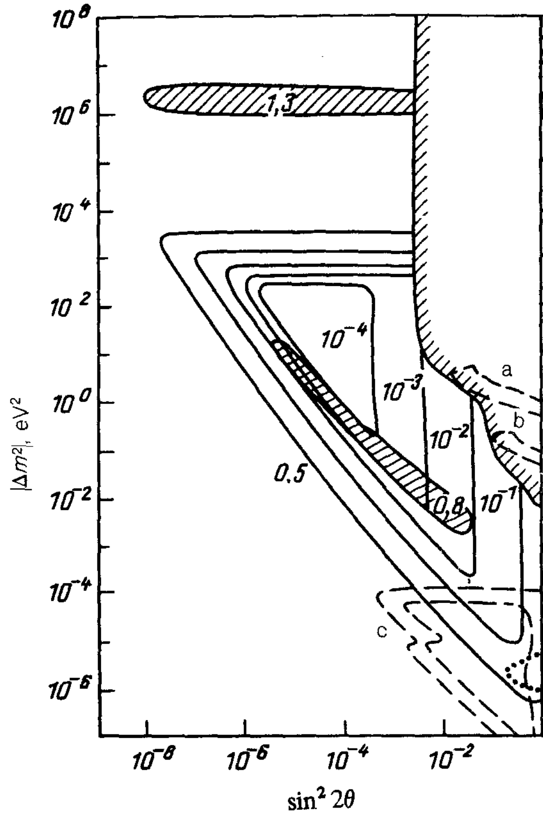

FIG. 1.

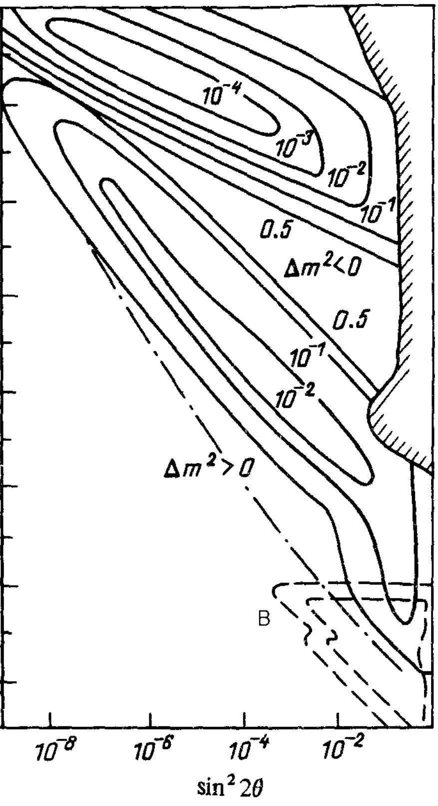

FIG. 2.

FIG. 1. Contour lines of the suppression of the energy of the ν_e burst from neutronization due to ν_e–ν_μ (ν_τ) oscillations (solid lines; the lines are labeled with the magnitude of the suppression). The regions of an asymmetric exchange of ν_e and ν_μ spectra in the stage of neutrino opacity are hatched. In the upper region we have $R > 1.3$, and in the lower region $R < 0.8$. Dashed lines: a—region of positive PS191 results; b—region of positive BUGEY results; c—region of solutions of the solar-neutrino problem. Dotted line—boundary of the region with an effect $R < 0.5$ at the earth for the Baksan apparatus. Dashed line—laboratory limitations.

FIG. 2. Contour lines of the suppression of the energy of a $\bar{\nu}_e$ burst due to $\bar{\nu}_e - \bar{\nu}_s$ oscillations in the stage of ν opacity (B). The dot-dashed line shows a possible increase in the region with $\Delta m^2 > 0$ due to the ejection and expansion of an envelope.

$$R \geqslant 6\mathscr{E}_\nu^{\text{expt}}/\mathscr{E}_k, \tag{2a}$$

$$R \geqslant \mathscr{E}_\nu^{\text{expt}}/\mathscr{E}_T, \tag{2b}$$

$$R \geqslant \min\left[\mathscr{E}_{\bar{\nu}}^{\text{expt}}/\mathscr{E}_\nu^{\text{expt}}, \mathscr{E}_\nu^{\text{expt}}/\mathscr{E}_{\bar{\nu}}^{\text{expt}}\right], \tag{2c}$$

where $\mathscr{E}_\nu^{\text{expt}} = 4\pi L^2 N_\nu \overline{E}_\nu$, N_ν and $\overline{E}_\nu$ are the total number and average energy of the neutrinos detected ($\mathscr{E}_{\bar{\nu}}^{\rm expt}$ is the corresponding average energy for antineutrinos), L is the distance to the star, and $\mathscr{E}_k$ is the limiting energy release during the collapse (in the case of SN1987A, this limiting energy is apparently $\mathscr{E}_k \simeq 10\ M_\odot$). In (2b), we have $\mathscr{E}_T = 4\pi R_\nu^2 \times 7\sigma T_\nu^4/16$, where T_ν and R_ν are the temperature and radius of the neutrinosphere [$T_\nu \simeq 2\bar{E}_\nu/7$ and $R_\nu < 30$–100 km]. This estimate is based on the circumstance that over broad ranges of Δm^2 and $\sin^2 2\theta$ the oscillations lead to an equal suppression for all parts of the spectrum, without changing $\bar{E}_\nu$ or thus T_ν. The total energies of ν_e and $\bar{\nu}_e$ bursts are compared in (2c). In the absence of oscillations, we would have $\mathscr{E}_\nu \approx \mathscr{E}_{\bar{\nu}}$; resonant oscillations would change either the ν_e or the $\bar{\nu}_e$ signal.

If the events detected in Ref. 3 are interpreted as a signal from a collapse, then we would have $R \gtrsim 10^{-1}$ in any case according to criteria (2a) and (2b); the region of values of the parameters Δm^2 and $\sin^2\theta$ bounded by the line $a = 10^{-1}$ in Fig. 2 is thus ruled out. This result is important for a wide range of models with right-hand neutrino components. For example, admixtures in ν_e of neutrinos with masses of 100 eV and 1 keV at the levels of 10^{-3} and 10^{-6}, respectively, are ruled out. The positive result of the BUGEY experiment lies in the prohibited region ($\Delta m^2 > 0$).

If the first two pulses in Ref. 3 are interpreted as the scattering of ν_e due to neutronization involving electrons, and if it is assumed that the energy in the ν_e peak is suppressed by a factor no greater than two (the corresponding neutronization would be $< 10\ M_\odot$), then the region bounded by the line $a = 1/2$ in Fig. 1 would be ruled out. (The cross section for $\nu_\mu e$ scattering is one-sixth that for $\nu_e e$ scattering.) Falling in this region are the positive results of the BUGEY and PS191 experiments and part of the Δm^2, $\sin^2 2\theta$ region corresponding to an oscillation solution of the solar-neutrino problem.[9]

If Δm^2 and $\sin^2 2\theta$ are measured in new oscillation experiments and in new experiments on solar neutrinos, it will become possible to test the interpretation of the events observed at the underground installations[1–4] and to refine our understanding of the structure of a collapsing star.

3. In the Δm^2 and $\sin^2 2\theta$ regions in which there is no strong suppression of $\mathscr{E}_\nu$, resonant oscillations in the star and in the earth can explain certain aspects of the signals at the various installations. In particular, these oscillations would distort the neutrino spectrum if this spectrum fell at the edge of the suppression "bath," $P(E/\Delta m^2, \sin^2 2\theta)$. If resonant regions in the earth and in the star overlap, the effect of the earth would be of the nature of a regeneration; if these regions do not overlap, the effect would be of the nature of a suppression of the flux of original $\nu_e^{(-)}$ particles. At 7 h 35 min, SN1987A was at the following zenith angles: 110° (Kamiokande), 146° (Baksan), 156° (LSD), and 132° (IMB). The effect of the earth is small for the Kamiokande installation; the regeneration of the $\bar{\nu}_e$ flux may be important for the Baksan and LSD installations.

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