Neutrino decay solution of the solar neutrino problem revisited

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The neutrino decay solution of the solar neutrino problem is revisited in the context of majoron models. It is shown that for a particular range of parameters this scenario reconciles both the Homestake data and the Kamiokande data. The prediction for gallium detectors is also given. It is shown that the sensitivity of Borexino is sufficient to observe the solar $\bar{\nu}_e$ signal, which is the crucial prediction of this scenario, and to distinguish it from the alternative $\bar{\nu}_e$ signal provided by the hybrid models of neutrino oscillation and magnetic moment transitions.

A possible solution of the solar neutrino problem (SNP) appeals to the possibility of neutrino decay during the flight from the sum to the earth.[1-3] This idea can be proposed in the context of majoron models.[4] In order that the decay $\nu_2 \to \nu_1 + M$ occur during the neutrino transit time $t \simeq 500$ s, the majoron M should have sufficiently strong off-diagonal coupling ($g > 10^{-4}$) with the neutrino mass eigenstates $\nu_{1,2}$. Although the most familiar candidate, the triplet majoron, has been ruled out by LEP data, there is a variety of new singlet majoron models in which the $\bar{\nu}_1 \nu_2 M$ coupling can be sufficiently strong[5] (the existence of tree level off-diagonal coupling requires nontrivial symmetry properties that distinguish among the lepton families, as was emphasized in Ref. 6).

The observation of the $\bar{\nu}_e$ pulse from SN1987A rules out the solution of SNP with fast $\nu_e \to \nu_x + M$ decay.[1] However, the case where the neutrino mixing angle θ is substantial remains open: $\nu_e = c\nu_1 + s\nu_2$, $\nu_x = -s\nu_1 + c\nu_2$, where ν_x is ν_μ or ν_τ, and $c = \cos\theta$, $s = \sin\theta$. Even if only the component ν_1 reaches the earth because of the fast decay of ν_2, the ν_e signal does not vanish and it directly measures the neutrino mixing angle: $c^4 \simeq R_{Ar} \simeq 0.3$.[2,3] This is quite compatible with the SN1987A bound $c^4 \geqslant 0.1$ (Ref. 3).

In the present paper we show that this scenario can reconcile the Homestake and the Kamiokande results and does not conflict with the astrophysical constraints and terrestrial experiments. Definite predictions for the Ga–Ge experiments are also given. The central feature of this scenario is the appearance of a substantial flux of solar $\bar{\nu}_e$. We show that future low-threshold real-time detectors like Borexino/Borex[7] will be quite sensitive to this signal so as to confirm or rule out the ν-decay solution.

Let us analyze the fate of solar neutrino ν_e in the case of fast majoron decay of the ν_e component. The decay widths of ν_2 with energy $E \gg m_2 = m$ in the two channels $\nu_2 \to \nu_1 + M$ and $\nu_2 \to \bar{\nu}_1 + M$[*)] are equal. We assume that $m = m_2 \gg m_1$ and ignore the mass of the ν_1 state. The neutrino lifetime in the laboratory frame is

$\tau(E) = 16\pi E/g^2m^2$. The energy distributions (normalized to 1/2) of the secondary ν_1 and $\bar{\nu}_1$ are respectively

$$W_\nu(\epsilon, E) = \frac{\epsilon}{E^2}, \quad W_{\bar{\nu}}(\epsilon, E) = \frac{E-\epsilon}{E^2}, \tag{1}$$

where ϵ is the energy of the secondary neutrino. Equations (1) show the strong degradation of the final state energy: for $\nu_2 \to \nu_1 + M$ and $\nu_2 \to \bar{\nu}_1 + M$ decays, typically 1/3 and 2/3 of the initial neutrino energy E is taken away by the majoron.

The fluxes of ν_e, ν_x, $\bar{\nu}_e$, $\bar{\nu}_x$ which arrive on the earth ($t = 500$ s) are respectively

$$\Phi_e(E) = (c^4 + s^4 e^{-t/\tau(E)})\Phi(E) + c^2 s^2 \Phi_I(E), \quad \Phi_{\bar{e}}(E) = c^2 s^2 \Phi_{\bar{I}}(E),$$

$$\Phi_x(E) = c^2 s^2 (1 + e^{-t/\tau(E)})\Phi(E) + s^4 \Phi_I(E), \quad \Phi_{\bar{x}}(E) = s^4 \Phi_{\bar{I}}(E), \tag{2}$$

where $\Phi(E)$ is the differential ν_e flux expected from the standard solar model (SSM)[8] and $s^2\Phi_{I,\bar{I}}(E)$ are the fluxes of the secondary ν_1 and $\bar{\nu}_1$:

$$\Phi_{I,\bar{I}}(E) = \int_E^{E_{end}} dE' \Phi(E')[1 - e^{-t/\tau(E')}] W_{\nu,\bar{\nu}}(E, E'). \tag{3}$$

From these equations one can compute the response of any solar neutrino detector as a function of θ and $\tau_{10} = \tau(10 \text{ MeV})$ and compare with the experimental data: $500 \text{ s}/\tau_{10} = 1.5 \times 10^{-9}\ g^2m^2$.

For the Homestake[9] and Kamiokande[10] experiments the ratios of the observed signal to the expectations of SSM, averaged over the data-taking period, are respectively: $\langle R_{Ar} \rangle_{70-90} = 0.29 \pm 0.03$, $\langle R_K \rangle_{87-90} = 0.46 \pm 0.05 \pm 0.06$. In the range of parameters we can reconcile both the Homestake data and Kamiokande data. In Fig. 1 the 2σ contours are shown for both experiments. One can observe a large overlapping region (the hatched region) within the area allowed by the bounds on the neutrino lifetime and mixing angle. The bound on θ comes from the SN1987A neutrino signal,[3] while the restriction on τ_{10} is derived as a combination of the astrophysical bound, $g < 1.5 \times 10^{-3}$ (Ref. 11) and the bound on m^2 (as a function of θ) from the $\nu_e \to \nu_x$ and $\nu_e \to \nu_\mu$ oscillations.[12] In Figs. 2 and 3 the 1σ allowed region is also shown. Some comments are in order:

a) For small lifetime, $\tau_{10} \ll 500$ s, the signals depend only on the mixing angle θ, since all solar ν_2's decay before reaching the earth. In this regime (the vertical branch of the hatched region in Fig. 1) the flux of secondary ν_e's gives almost the same contribution to both experiments, and the difference in the signals is accounted mainly by the neutral current contribution for Kamiokande, which corresponds to the ν_x (ν_μ or ν_τ) flux.

b) For the lifetime $\tau_{10} \sim 500$ s (the horizontal branch of the hatched region) more energetic neutrinos are less suppressed due to the Lorentz factor. This "just so" decay

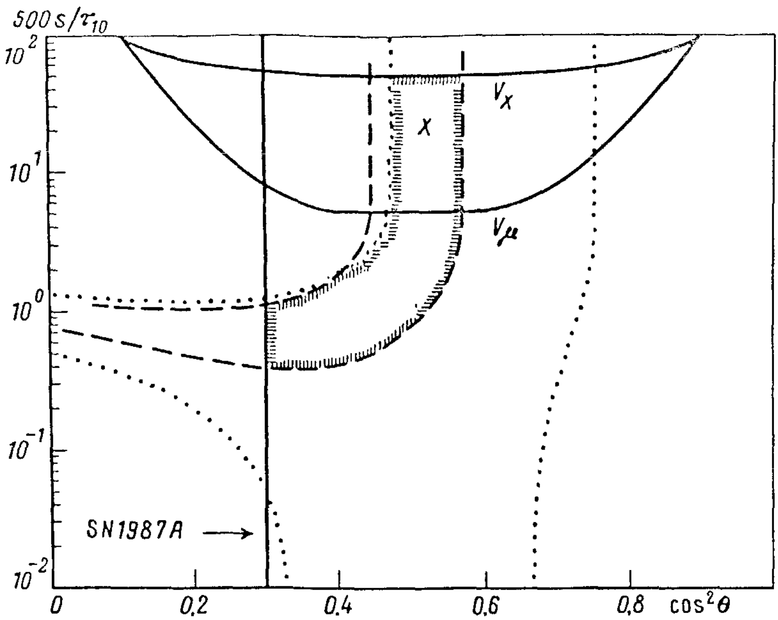

FIG. 1. In the plane of the mixing angle and neutrino lifetime we present the region of $\cos^2\theta$ not covered by the SN1987A data (to the left of the solid vertical line), the region of τ_{10} excluded for arbitrary ν_x state (above the ν_x line), the region of τ_{10} excluded for $\nu_x = \nu_\mu$ (above the ν_μ line), the region allowed by the Homestake experiment at 2σ level (inside the dashed curves) and the region allowed by the Kamioka experiment, at 2σ level (inside the dotted curves). All constraints intersect within the hatched area. The subregion excluded for $\nu_x = \nu_\mu$ is denoted by X.

accounts for the main difference in the signals of these two detectors because of the different energy thresholds.

We also computed the response of Ga–Ge detectors. The contours corresponding to the different ratios of ^{71}Ge production rate with respect to the SSM central value (132 SNU)[8] are shown in Fig. 2. Note that in the region of τ_{10}, which is relevant for SNP, the germanium signal depends mainly on θ, since low-energy neutrinos are most important. According to the hatched region, we have $R_{\rm Ge} = 0.15$–0.36, consistent with the preliminary results of the SAGE experiment $\langle R_{\rm Ge}\rangle_{90\text{-}91} < 72$ SNU (90% c.l.).[13]

The range of parameters relevant for the solution of SNP corresponds to $c^2 = 0.3$–0.6 and $\tau_{10} < 1000$ s. In this case, according to Eqs. (2) and (3), a substantial part ($\sim 10\%$) of the solar neutrinos should decay into $\bar{\nu}_e$. The Kamiokande detector is not sensitive to this $\bar{\nu}_e$ flux because of the strong degradation of the energy spectrum. However, the planned low threshold, free proton-rich detectors like Borexino/Borex will be quite sensitive to these $\bar{\nu}_e$'s. We consider, for example, 100 tons of the liquid scintillator, which corresponds to the fiducial volume of Borexino.[7] In Fig. 3 the total number of solar $\bar{\nu}_e$ reactions above the energy cutoff $E = 5$ MeV ($E_+ = 3.7$ MeV for the positron energy) is plotted as a function of θ and τ_{10}. As we can see, for

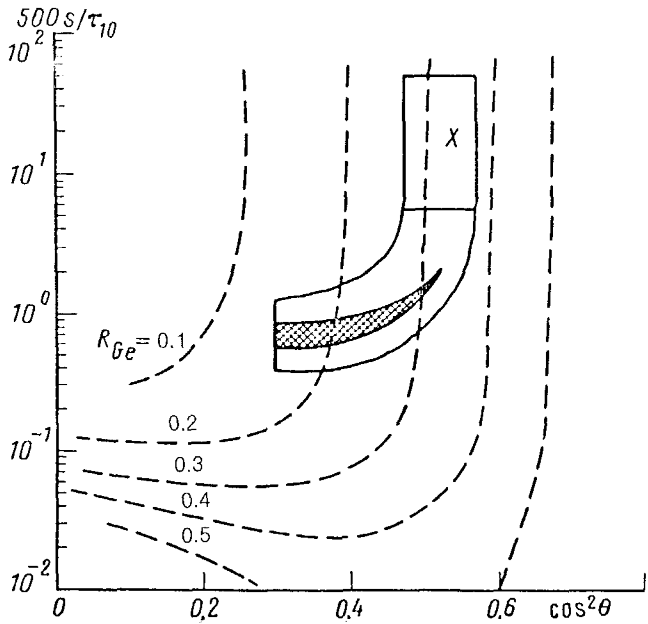

FIG. 2. The expectation for gallium experiments. Isosignal curves corresponding to different values of R_{Ge} are shown. The area relevant for the SNP at 2σ level is within the solid curve. 1σ level region is also shown (shaded). The subregion excluded for $\nu_x = \nu_\mu$ is denoted by X.

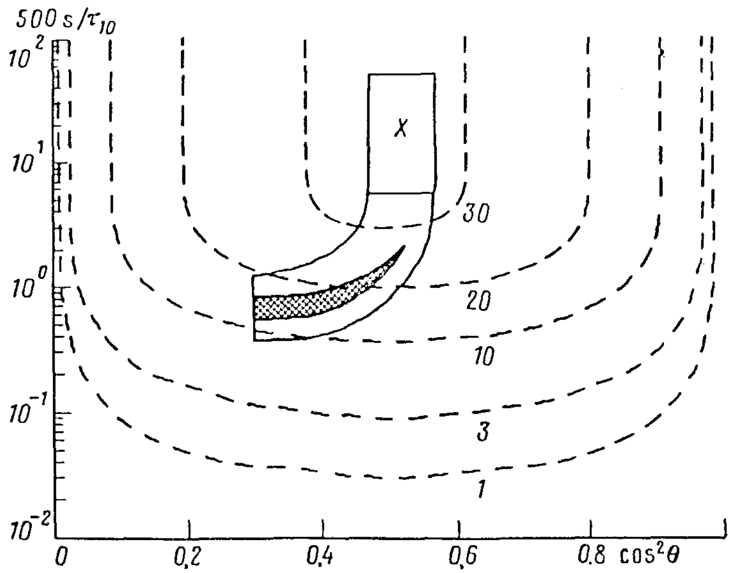

FIG. 3. Isosignal curves corresponding to the number of $\bar{\nu}_e + p \rightarrow n + e^+$ interactions per year in Borexino, for a fiducial mass of $100t$ and positron energy cutoff $E_+ = 3.7$ MeV. The area relevant for the SNP is enclosed by the solid line; the notation is the same as in Fig. 2.

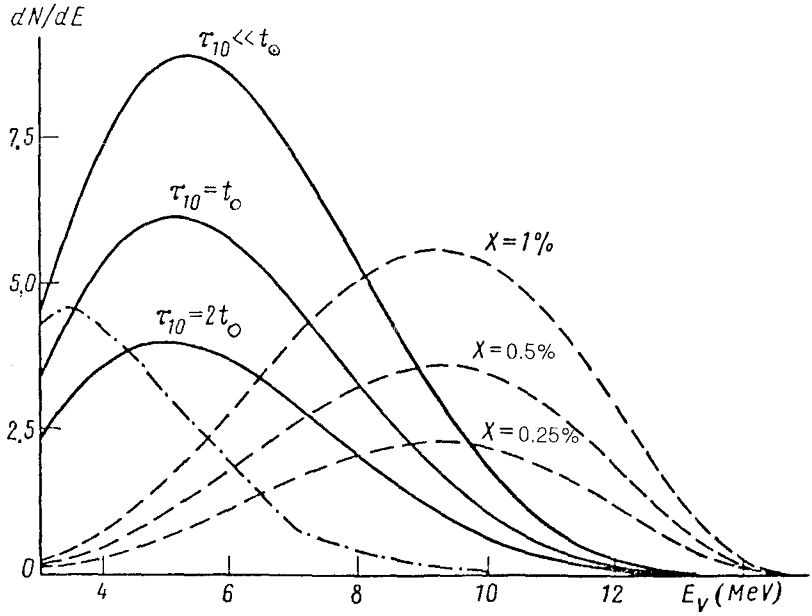

FIG. 4. Energy distribution of $\bar{\nu}_e + p \to n + e^+$ interactions per year in Borexino, for a fiducial mass of 100 t: a) due to the reactor background (dot-dashed line), b) due to the solar $\bar{\nu}_e$ flux from the ν decay, for $\theta = 45°$, and different values of τ_{10}, solid lines, c) due to the solar $\bar{\nu}_e$ flux for the case where a percentage x of solar neutrinos is converted to $\bar{\nu}_e$ due to the magnetic moment transition, dashed lines. Assuming $E_+ = 3.7$ MeV, the total number of interactions is 5 events for a) and 32, 21, and 10 events, respectively, for the three curves of b) and c).

the region corresponding to SNP, about 10–30 interactions per year are predicted. We note that the reactor antineutrino contribution, which is considered as the main source of the background, is very low, $\sim$3–5 reactions per year.[7]

The appearance of solar antineutrinos is also predicted in the context of so-called hybrid models as a result of the combined effect of resonant oscillations and spin-flavor precession of Majorana neutrinos.[14,15] Such a possibility was suggested essentially for the explanation of the time variation of the solar neutrino flux in anticorrelation with solar magnetic activity. In this scenario, the $\bar{\nu}_e$ energy spectrum should not be significantly altered as compared to the initial solar ν_e spectrum. The ratio $\Phi_{\bar{e}}/\Phi$ is predicted at the level of few percents.[15] A rather conservative experimental upper bound, $\Phi_{\bar{e}}/\Phi < 6\%$, was derived from Kamiokande data by assuming that all the background is due to solar $\bar{\nu}_e$'s.[16] This bound could be improved by taking into account the conventional background sources. Note, however, that $\Phi_{\bar{e}}/\Phi = 1\%$ corresponds to about 30 events/yr for Borexino.

Borexino sensitivity makes it possible to discriminate clearly between these two solutions of SNP. In Fig. 4 the energy distribution of $\bar{\nu}_e p$ interactions is shown for the antineutrinos from the decay and from the hybrid model, for some values of the parameters. The parameters have been chosen so as to give the same number of events in the two scenarios for a positron energy threshold $E_+ = 3.7$ MeV. The $\bar{\nu}_e$ energy spectra can be clearly discriminated. For comparison, the energy distribution of the reactor $\bar{\nu}_e$ interactions is also shown.

Another important feature of the hybrid scenario is the prediction of direct correlation of solar $\bar{\nu}_e$ flux with solar activity. However, a large exposition time is required to establish this correlation ($\sim$6–10 years).

Before concluding, the following comment is in order. The hybrid model will not produce a $\bar{\nu}_e$ signal if the conservation of some lepton number takes place[17] ($L_\pm = L_e \pm L_\mu \mp L_\tau$). This also holds for the case of neutrino decay. Even in this case the decay scenario can be distinguished from others by looking at neutral current signals: because of the energy degradation of secondary neutrinos, it must be significantly weaker (by at least a factor 2) compared with the oscillations and magnetic moment transition scenarios.

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*) In the case of Majorana neutrinos, we identify the states of neutrino ν and antineutrino $\bar{\nu}$ as states with negative and positive helicities, respectively.

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