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THE NEUTRINO DECAY SOLUTION TO 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 definite range of parameters this scenario reconciles both the Homestake 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 hybrid models of neutrino oscillation and magnetic moment transitions.

One of the possible solutions of the solar neutrino problem (SNP) appeals to the possibility of neutrino decay during the flight from sun to earth [1-3]. This idea can be proposed in the context of majoron models [4]. In order that the decay $\nu_2 \to \nu_1 + M$ occurs during the neutrino transit time $t \simeq 500s$, 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, a variety of new singlet majoron models can be considered, in which the $\bar{\nu}_1 \nu_2 M$ coupling can be sufficently strong [5] (The existence of tree level off-diagonal couplings requires non-trivial symmetry properties distinguishing among the lepton families, as was emphasized in [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 when 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 earth owing to the fast decay of ν_2, the ν_e signal is not vanishing 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 $c^4 \geq 0.1$ [3].

In the present paper we show that this scenario can reconcile the Homestake and the Kamiokande results and does not conflict with astrophysical constraints and terrestrial experiments. Definite predictions for 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 analyse the fate of solar ν_e in the case of fast majoron decay of ν_e component. The decay width of ν_2 with energy $E \gg m_2 = m$ in the two channels $\nu_2 \to \nu_1 + M$ and $\nu_2 \to \bar{\nu}_1 + M$ [4)] are equal. We assume that $m = m_2 \gg m_1$

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

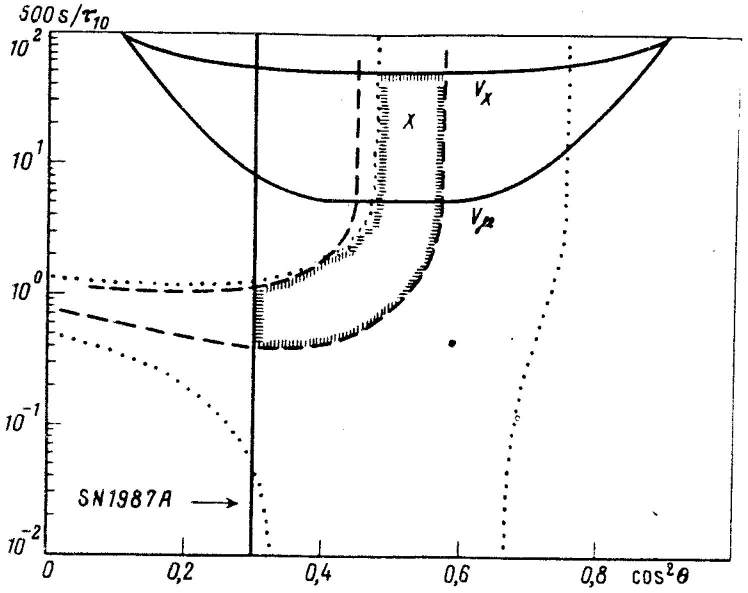

Fig.1. In the plane of mixing angle and neutrino lifetime we present: the region of $\cos^2\theta$ excluded by the SN1987A data (to the left of the solid vertical line), the region of τ_{10} excluded for arbitrary ν_x state (above the ν_x line), the region of τ_{10} excluded for $\nu_x = \nu_\mu$ (above 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). The intersection between all constraints is within the shaded area. The subregion excluded for $\nu_x = \nu_\mu$ is denoted by X

and neglect the mass of the ν_1 state. The neutrino lifetime in the lab frame is $\tau(E) = 16\pi E/g^2m^2$. The energy distributions (normalized to 1/2) of 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. Eqs. (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, $\bar{\nu}_e$, $\bar{\nu}_x$ arriving on the earth ($t = 500s$) are respectively:

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

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

where $\Phi(E)$ is the differential ν_e flux expected from standard solar model (SSM)[8]

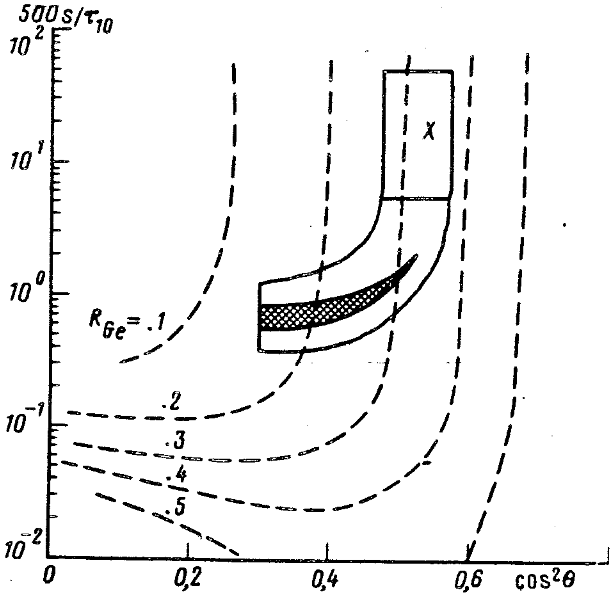

Fig.2. The expectation for Gallium experiments. Isosignal curves corresponding to different values of R_{Ge} are shown. The area relevant for the SNP at 2σ level is within the solid curve. 1σ level region is also shown (shaded). The subregion excluded for $\nu_x = \nu_\mu$ is denoted by X.

and $s^2\Phi_{I,J}(E)$ are the fluxes of secondary $\nu_1, \bar{\nu}_1$:

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

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

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

a) for small lifetime, $\tau_{10} \ll 500s$, the signals depend only on the mixing angle θ since all solar ν_2's decay before reaching the earth. In this regime (vertical branch of the shaded area in Fig.1) the flux of secondary ν_e's gives almost the same

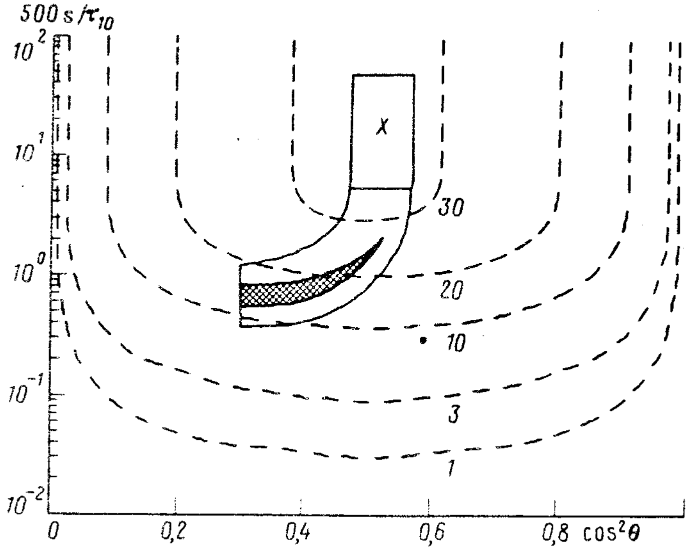

Fig.3. Isosignal curves corresponding to the number of $\bar{\nu}_e + p \rightarrow n + e^+$ interactions per year in Borexino, for a fiducial mass of 100t and positron energy cutoff $E_+ = 3.7$ MeV. The area relevant for the SNP is within the solid line, same notation as in fig.2.

contribution to both experiments and the difference among the signals is provided mainly by the neutral current contribution for Kamiokande, corresponding to ν_x (ν_μ or ν_τ) flux.

b) For lifetime $\tau_{10} \sim 500s$ (horizontal branch of the shaded area) more energetic neutrinos are less suppressed due to the Lorentz factor. This "just so" decay provides the main difference between the signals of these two detectors due to the different energy thresholds.

We also computed the response of Ga-Ge detectors. In Fig.2 the contours corresponding to different ratios of ^{71}Ge production rate with respect to the SSM central value (132 SNU) [8] are shown. 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. In correspondence to the shaded area we have $R_{\rm Ge} = 0.15 \div 0.36$. This is compatible with the preliminary results of the SAGE experiment $\langle R_{\rm Ge} \rangle_{90\div91} < 72$ SNU (90%$c.l.$) [13].

The range of parameters relevant for the solution of SNP corresponds to $c^2 = 0.3 \div 0.6$ and $\tau_{10} < 1000s$. In this case, according to eqs. (2,3), a substantial part ($\sim$ 10%) of solar neutrinos should decay into $\bar{\nu}_e$. The Kamiokande detector is not sensitive to this $\bar{\nu}_e$ flux due to the strong degradation of the energy spectrum. However, the planned low threshold, free proton rich detectors like Borexino/Borex will be quite sensitive to this $\bar{\nu}_e$'s. As an example, we consider 100 tons of liquid scintillator corresponding 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 depicted as a function of θ and

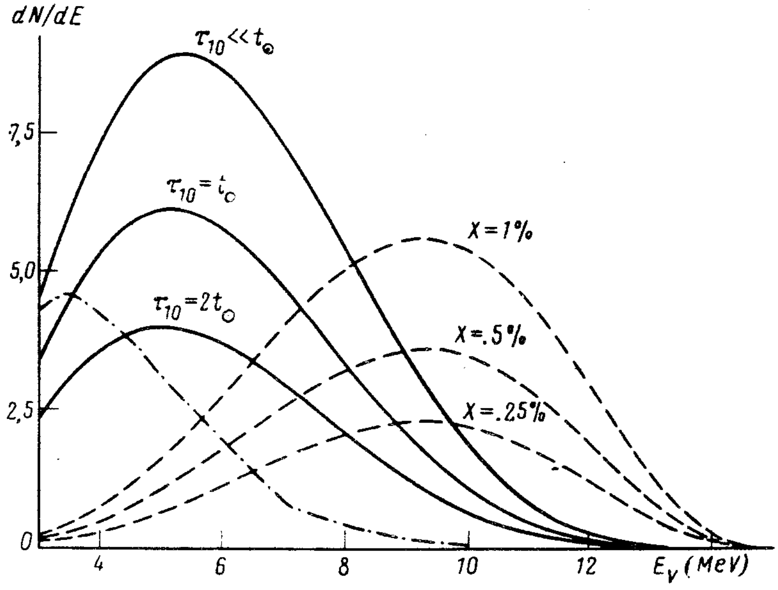

Fig.4. Energy distribution of $\bar{\nu}_e + p \rightarrow n + e^+$ interactions per year in Borexino, for a fiducial mass of 100 t: *a)* due to reactor background (dot-dashed line), *b)* due to solar $\bar{\nu}_e$ flux from ν-decay, for $\theta = 45°$, and different values of τ_{10}, solid lines, *c)* due to solar $\bar{\nu}_e$ flux for the case that a percentage x of solar neutrinos are converted to $\bar{\nu}_e$ due to 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).

τ_{10}. As we see, for the region corresponding to SNP, about $10 \div 30$ interactions per year are predicted. We note that the reactor antineutrino contribution, wich is considered as a main source of background, is very low, $\sim 3 \div 5$ reactions per year [7].

The appearence of solar antineutrinos is predicted also in the context of so called hybrid models as a result of the combined effect of resonant oscillations and spin-flavour 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 conventional background sources. Note however, that $\Phi_{\bar{e}}/\Phi = 1\%$ corresponds to about 30 events/yr for Borexino.

Borexino sensitivity allows to discriminate clearly between these two solution 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 choosen 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 reactor $\bar{\nu}_e$ interactions is also shown.

We would like to remark that another important feature of the hybrid scenario is the prediction of direct correlation of solar $\bar{\nu}_e$ flux with solar activity. However, to establish this correlation large exposition time is required ($\sim 6 \div 10$ years).

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

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