RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 43, NUMBER 6 15 MARCH 1991

Sterile-neutrino solutions to the solar puzzle

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(Received 13 December 1990)

We find solutions to the solar-neutrino problem in which ν_e has resonant oscillations in the Sun with a sterile neutrino ν_x. We show that the $\nu_e \rightarrow \nu_x$ oscillation scenario can be distinguished from standard $\nu_e \rightarrow \nu_\mu$ (or ν_τ) resonant oscillations by measurements of ν_e capture on ^{71}Ga, low-energy ν-e scattering ($E_\nu \sim 1$ MeV), and ν neutral-current interactions on nuclei.

Matter-enhanced neutrino oscillations in the Sun [the Mikheyev-Smirnov-Wolfenstein (MSW) effect[1]] are an attractive explanation[2-5] for the observed suppression of the solar-neutrino flux[5,6] relative to the standard solar model[7] (SSM). Recent quantitative analyses have shown that the results from the ^{37}Cl Homestake mine experiment[6] and from the Kamiokande II (K II) ν-e scattering detector[5] can be consistently explained by the MSW effect[3-5] or by long-wavelength vacuum oscillations.[8] Previous considerations of the MSW effect have assumed $\nu_e \rightarrow \nu_\mu$ (or ν_τ) oscillations. In the present Rapid Communication we address the possibility of an MSW explanation based on $\nu_e \rightarrow \nu_x$ oscillations, where ν_x is a sterile neutrino (i.e., ν_x has no $\mathrm{SU}(2)_L \times U(1)$ electroweak interactions); such neutrinos are present in many extended gauge models. With $\nu_e \rightarrow \nu_x$ oscillations the propagation equations for neutrinos in matter differ from the $\nu_e \rightarrow \nu_\mu$ case, due to the different neutral-current (NC) interactions of ν_e and ν_x with matter; the other significant difference is that detectors designed to measure NC interactions (such as BOREX[9] and SNO[10]) will not detect ν_x but will detect ν_μ or ν_τ. In the $\nu_e \rightarrow \nu_\mu$ case the refractive indices due to NC scattering are irrelevant, since a common overall phase of the neutrino wave functions is unobservable. In the $\nu_e \rightarrow \nu_x$ case the difference of NC refractive indices produces significant changes in the propagation. We find that the general features of matter-enhanced neutrino oscillations survive and that it is still possible to consistently explain both the Homestake and K II results with $\nu_e \rightarrow \nu_x$; however, the predictions of these solutions for the ^{71}Ga, BOREXINO, and SNO experiments[9-12] are changed, and thus the $\nu_e \rightarrow \nu_x$ and $\nu_e \rightarrow \nu_\mu$ MSW possibilities can be experimentally differentiated.

In the presence of matter, the equation for two-neutrino propagation in the (ν_{eL}, ν_{xL}) basis is

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \frac{1}{4E_\nu}\begin{pmatrix} 4\sqrt{2}G_F E_\nu \left(N_e - \frac{1}{2}N_n\right) & \delta m^2 \sin 2\theta \\ \delta m^2 \sin 2\theta & 2\delta m^2 \cos 2\theta \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}, \tag{1}$$

where N_e and N_n are the electron and neutron number densities in matter, E_ν is neutrino energy, δm^2 is the difference of neutrino mass eigenvalues squared, and θ is the vacuum mixing angle in the (ν_e, ν_x) sector. The only difference here from the familiar $\nu_e \rightarrow \nu_\mu$ case is the appearance[13] of N_n in Eq. (1).

The MSW effect relies on the existence of a resonance in the local oscillation amplitude in matter:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\lambda_v/\lambda_0 - \cos 2\theta)^2 + \sin^2 2\theta}, \tag{2}$$

where $\lambda_v = 4\pi E_\nu/\delta m^2$ is the vacuum oscillation length and $\lambda_0 = \sqrt{2}\pi/(G_F N_{\text{eff}})$ with $N_{\text{eff}} = N_e - \frac{1}{2}N_n$ in the $\nu_e \to \nu_x$ case and $N_{\text{eff}} = N_e$ in the $\nu_e \to \nu_\mu$ case. Thus the condition for the existence of a resonance as a ν_e of energy E_ν propagates through the Sun is $\lambda_v/\lambda_0 = 2\sqrt{2}G_F E_\nu N_{\text{eff}}/\delta m^2 > \cos 2\theta$, where N_{eff} is evaluated at the initial position of the neutrino. In the $\nu_e \to \nu_\mu$ case, the combined analysis of Homestake and KII data leads to a wishbone-shaped region of solutions in the $(\delta m^2, \sin^2 2\theta/\cos 2\theta)$ plane, with one vertical branch around $\sin^2 2\theta/\cos 2\theta \sim$ 1–4 extending up to $\delta m^2 \sim 10^{-4}\,\text{eV}^2$ and one diagonal branch with $\delta m^2\theta^2 \sim 10^{-8}\,\text{eV}^2$ extending up to $\delta m^2 \sim 10^{-5}\,\text{eV}^2$. These upper limits are set by the resonance condition. Qualitatively, we therefore expect that the corresponding solution branches in the $\nu_e \to \nu_x$ case will not extend as high in δm^2, since N_{eff} is smaller. Other regions of the MSW wishbone will also be shifted somewhat, because the densities N_e and N_n do not precisely track each other in the Sun.

The SSM densities[7] have been calculated in tabular form. We find the following analytic expression to be a good fit for the densities:

$$N = N(0)\exp\left(-\frac{1}{z_0}\frac{z^2}{z+b}\right), \tag{3}$$

where $z = r/R_\odot$. The parameters for N_e, N_n, and $N_e - \frac{1}{2}N_n$, respectively, are $N(0)/N_A = 98.8, 48.4, 74.6$, and $b = 0.15, 0.02, 0.20$ with $z_0 = 0.09$ in all cases. The logarithmic derivative $d(\ln N_{\text{eff}})/dr$ does not greatly differ between the N_e and $N_e - \frac{1}{2}N_n$ cases. Hence there will be little change in the adiabatic condition $C/E_\nu \gg 1$, where

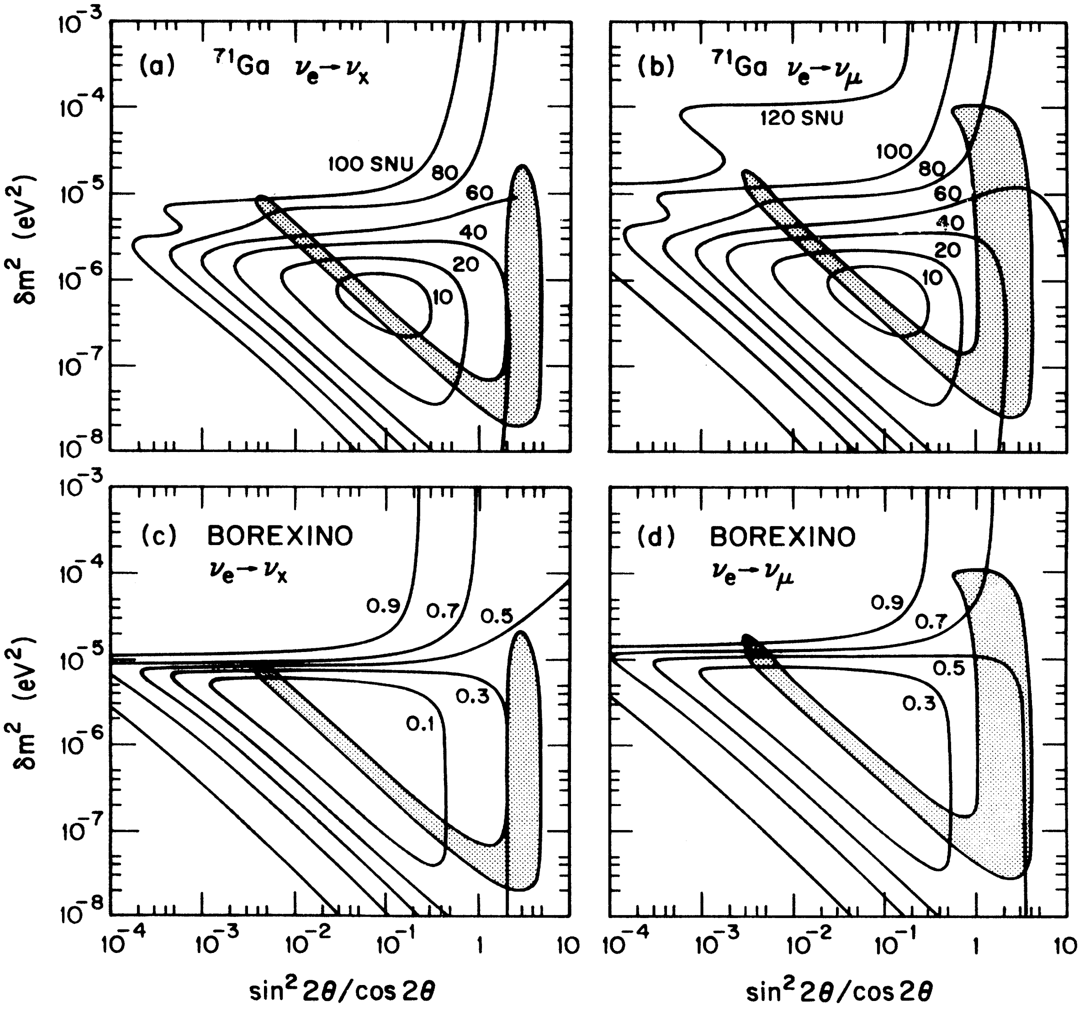

FIG. 1. Contours of expected interaction rate for ^{71}Ga experiments for (a) $\nu_e \to \nu_x$ and (b) $\nu_e \to \nu_\mu$, and contours of expected suppression ratio (interaction rate compared to SSM prediction) for ν-e scattering in the BOREXINO experiment for (c) $\nu_e \to \nu_x$ and (d) $\nu_e \to \nu_\mu$, shown versus oscillation parameters $\sin^2 2\theta/\cos 2\theta$ and δm^2. The regions allowed by the ^{37}Cl and KII data at 95% C.L. have been shaded. With no suppression the SSM ^{71}Ga rate would be 132 SNU.

$$C=\frac{\pi}{4}\frac{\delta m^2 \sin^2 2\theta}{\cos 2\theta}\left|\frac{d(\ln N_{\rm eff})}{dr}\right|^{-1} . \qquad (4)$$

Similarly the nonadiabatic transition probability between matter eigenstates $P_x = \exp(-C/E_\nu)$ is little changed, for the same δm^2 and θ values.

We have made a quantitative analysis of $\nu_e \to \nu_x$ MSW solutions to the Homestake and KII data (following the work of some of the present authors in the $\nu_e \to \nu_\mu$ case[3]). The allowed region at 95% C.L. in $\sin^2 2\theta/\cos 2\theta$ versus δm^2 parameter space is shown by the shaded area in Figs. 1(a) and 1(c). For comparison, the shaded areas in Figs. 1(b) and 1(d) show the corresponding allowed region in the $\nu_e \to \nu_\mu$ case.[3] These results substantiate the qualitative discussion given above. Figures 1(a) and (b) compare the $\nu_e \to \nu_x$ and $\nu_e \to \nu_\mu$ predictions for ν_e capture on ^{71}Ga. Preliminary results from the SAGE ^{71}Ga experiment[11] give data/SSM $= 0.0 \pm 0.5$, where the SSM prediction here is 132 solar-neutrino units (SNU). The range of SAGE predictions is almost the same in both cases. Figures 1(c) and 1(d) compare the $\nu_e \to \nu_x$ and $\nu_e \to \nu_\mu$ predictions for low-energy ν-e scattering ($E_\nu \sim 1$ MeV) in the BOREXINO[9] experiment; we note that the range of BOREXINO predictions is substantially lower in the $\nu_e \to \nu_x$ case. As an additional means of discriminating between the $\nu_e \to \nu_x$ and $\nu_e \to \nu_\mu$ solutions, we compare the correlations between the ^{71}Ga and BOREXINO predictions in Fig. 2.

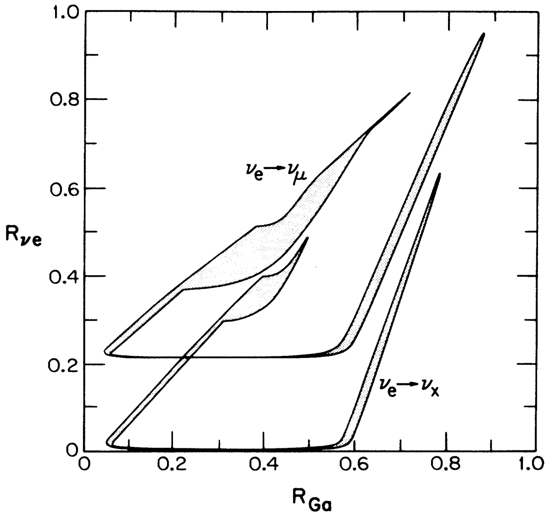

FIG. 2. Correlation of the suppression ratios $R_{\rm Ga}$ in ^{71}Ga experiments and $R_{\nu e}$ for ν-e scattering in BOREXINO, for the $\nu_e \to \nu_x$ and $\nu_e \to \nu_\mu$ scenarios. The shaded regions are allowed at 95% C.L. by the ^{37}Cl and KII data.

Eventually, measurements of neutrino NC interactions with nuclei will be possible at the Sudbury Neutrino Observatory[10] (SNO) and BOREX[9] detectors. These experiments will measure the higher-energy neutrinos, which come largely from ^{8}B. Since ν_x is sterile and has no NC interactions, NC and CC results will be equally suppressed for the $\nu_e \to \nu_x$ scenario. The ^{37}Cl and KII data suggest[3] that the CC rates for higher-energy neutrinos are suppressed by a factor of approximately 0.4 compared to the SSM. We could then expect the following results in the two scenarios:

$$\begin{aligned} &{\rm NC} \simeq 0.4, \quad {\rm CC} \simeq 0.4, \quad {\rm NC/CC} \simeq 1 \quad \text{for } \nu_e \to \nu_x , \\ &{\rm NC} \simeq 1, \quad {\rm CC} \simeq 0.4, \quad {\rm NC/CC} \simeq 2.5 \quad \text{for } \nu_e \to \nu_\mu , \end{aligned} \qquad (5)$$

where NC and CC rates are given as fractions of SSM expectations.

This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the U.S. Department of Energy under Contracts Nos. DE-AC02-76ER00881, DE-FG06-85ER40224, and W-7405-Eng-82, Office of Energy Research (KA-01-01), Division of High Energy and Nuclear Physics, and by the Texas National Research Laboratory.

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