LONG-WAVELENGTH OSCILLATIONS AND
THE GALLEX SOLAR NEUTRINO SIGNAL

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ABSTRACT

The recently reported solar neutrino signal in the \(^{71}\)Ga GALLEX detector adds a new dimension to the solar neutrino puzzle, complementing the previously known signals in \(^{37}\)Cl and water-Cherenkov detectors. Possible explanations for this new signal in terms of matter-enhanced neutrino oscillations (MSW effect) are already awaiting in the literature. We point out here that long-wavelength vacuum oscillations can furnish an alternative explanation of all three signals simultaneously; such solutions give neutrino spectra with distinctive energy dependence and seasonal time dependence.
The recent observation of a solar neutrino signal in the $^{71}$Ga detector of the GALLEX group has added an important new constraint in the solar neutrino puzzle. Going beyond early upper limits and recent more positive indications from the SAGE group, that uses a different technique based on metallic gallium, GALLEX reports a definite signal of $83 \pm 19 \pm 5$ SNU to be compared with predictions of about 132 SNU in the standard solar model (SSM) with conventional neutrino propagation. This indicates a suppression ratio

$$R_{Ga} = \frac{\text{observed Ga rate}}{\text{SSM Ga rate}} = 0.63 \pm 0.16$$

relative to the latest Bahcall-Pinsonneault calculation, that differs from the corresponding suppression ratios

$$R_{Cl} = 0.26 \pm 0.05, \quad R_{Kam II} = 0.47 \pm 0.09,$$

in the classic $^{37}$Cl Homestake detector and in the water Cherenkov ($\nu$-e scattering) Kamiokande II detector, that have higher neutrino energy thresholds. Both experimental and theoretical errors are included here. The new solar neutrino puzzle is to explain these three different observations simultaneously.

A first discussion, presented by the GALLEX group itself and amplified by others, argues that an explanation in terms of non-standard solar models is still at least conceivable, although not particularly promising. They also show that explanations in terms of matter-enhanced neutrino oscillations (the MSW effect) are possible, for two distinct regions in the $(\sin^2 2\theta, \delta m^2)$ parameter plane. Indeed, several authors have previously studied MSW fits to the Homestake and Kamiokande II data simultaneously via mixing with active or sterile neutrino species; their solutions broadly agree, their range of predictions for the gallium experiment exist in the literature and already indicate where the new GALLEX result can be accommodated in a MSW scenario.

In the present Letter we point out an alternative explanation in terms of long-wavelength vacuum neutrino oscillations; solutions of this kind, previously fitted to the Homestake and Kamiokande data, predict $^{71}$Ga capture rates quite consistent with the new GALLEX result above.
With such oscillations, having wavelengths comparable to the Earth-Sun distance, it is natural for some sections of the solar neutrino spectrum to be greatly suppressed while others suffer less suppression. In the following we shall first present updated long-wavelength oscillation (LWO) fits to the Homestake plus Kamiokande data, using the most recent version of the SSM [4] and incorporating the first 220 days preliminary results from the upgraded Kamiokande III detector [20], that give

$$R_{\text{Kam III}} = 0.60^{+0.15}_{-0.13}. \quad (3)$$

Superposing these solutions on an iso-SNU plot of the corresponding predictions of a $^{71}\text{Ga}$ detector exhibits visually the range of GALLEX predictions that is allowed for this kind of solution and the neutrino mass and mixing parameters that are required. Finally, we shall present LWO fits to the Homestake plus Kamiokande plus GALLEX data simultaneously and discuss their predictions for future observations.

We have first re-fitted the LWO hypothesis to the latest suppression ratios from Homestake and Kamiokande III (above), together with the Kamiokande II ratios separated into 14 bins of recoil electron energy $T_e$ (their weighted mean appears in Eq. (2)), in order to input the maximal pre-GALLEX spectral information. The initial solar neutrino spectrum is taken from the recent Bahcall-Pinsonneault [4] update of the SSM, that includes He diffusion and other improvements on previous calculations [3]. We assume two-flavor mixing of the electron-neutrino $\nu_e$, either with an active neutrino species $\nu_\alpha$ ($\alpha = \mu$ or $\tau$) or with a sterile neutrino $\nu_X$; these two scenarios are indistinguishable in $^{37}\text{Cl}$ or $^{71}\text{Ga}$ detectors, but give different results in detectors (including Kamiokande) that are sensitive to neutral-current scattering of $\nu_\alpha$. Figure [4] shows our resulting regions of fit in the $(\sin^2 2\theta, \delta m^2)$ plane, where $\theta$ is the usual mixing angle and $\delta m^2$ is the difference of mass-squared eigenvalues. There are 16 data points ($\text{Cl rate}$, 14 $T_e$ bins from Kam II, Kam III rate) and two free parameters; the best fit was for $\nu_e-\nu_\alpha$ oscillations with $\delta m^2 = 6.4 \times 10^{-11} \text{eV}^2$ and $\sin^2 2\theta = 0.83$, yielding $\chi^2_{\text{min}} = 12.5$. The regions of fit have summed $\chi^2 < \chi^2_{\text{min}} + 6.1$ corresponding to 95% CL. As in previous fits [11,17,19], we see that sterile-neutrino mixing solutions are more restricted but not excluded. We note that $\nu_e-\nu_X$ oscillations with maximal mixing are an essential
feature of a recent custom-designed model [21] for the controversial 17 keV neutrino; in such models LWO are then preferable to MSW solutions as an explanation for the solar neutrino puzzle.

Figure I also shows time-averaged iso-SNU contours for the $^{71}$Ga capture rate. We see that the LWO regions of fit to Homestake and Kamiokande data fall almost entirely between the 60 SNU and 80 SNU contours, predicting $^{71}$Ga capture rates compatible both with the GALLEX signal of $83 \pm 19 \pm 5$ SNU [1] and with the published SAGE upper limit of 79 SNU [2] at 90% CL (compatibility with SAGE data alone was previously discussed in Ref. [19]). This figure shows that the LWO hypothesis accommodates the present gallium data quite naturally. It also shows how a future more precisely determined $^{71}$Ga rate can fit in.

Finally we have fitted the LWO hypothesis to all Homestake plus Kamiokande plus GALLEX results combined (17 data points with two free parameters); the best fit parameters are nearly identical to those in the fit without the GALLEX result, and give $\chi^2_{\text{min}} = 13.7$. Figure 2 shows the corresponding regions of fit at 95% CL in the ($\sin^2 2\theta$, $\delta m^2$) plane. These regions summarize the LWO picture for present data.

The LWO predictions for future experiments are particularly sensitive to line sources in the solar neutrino spectrum, such as the 862 keV $^7$Be line (that generates most of the wiggles in the $^{71}$Ga contours in Fig. I). Observations of $\nu_e$-e scattering at the planned BOREXINO detector [22], in the electron recoil energy band $0.26 < T_e < 0.66$ MeV, will be very sensitive to this $^7$Be line contribution. Figure 2 shows contours of the time-averaged suppression factor $R(\text{Borexino})$ for this energy band; a range of possible values $0.3 \lesssim R \lesssim 0.9$ is allowed for $\nu_e$-$\nu_\alpha$ active neutrino oscillations, or a range $0.1 \lesssim R \lesssim 0.4$ for $\nu_e$-$\nu_X$ sterile neutrino oscillations. These are quite wide bands, that fully overlap the range 0.21–0.65 expected for MSW solutions [8,11]; unless the BOREXINO results lie outside the MSW band, or future data make the bands much narrower, this time-averaged measurement alone will not discriminate sharply between MSW and LWO solutions. One may also look at higher $T_e$ values, which contain contributions from pep, $^{13}$N and $^{15}$O neutrinos, but there the number of events is smaller by an order of magnitude and the statistical uncertainties correspondingly greater.

A distinctive feature of LWO scenarios, however, is that they contain clean and potentially resolvable oscillations in the $\nu_e$ survival probability $P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2(\delta m^2 L/4E)$, where
$L$ is the distance from source to detector; this feature is absent in MSW scenarios with larger $\delta m^2$ values where the corresponding oscillatory factors are averaged due to the size of the solar source. An immediate consequence is a time dependence of the contributions from line sources, due to the seasonal changes in the Earth-Sun distance [14–19]; here we fix $E$ and find $L$ dependence in $P(\nu_e \to \nu_e)$. Eventually, it should be possible to discriminate between LWO and other explanations on this basis alone, but at present there is little evidence on this score. The $^{37}$Cl capture rate has a $^7$Be component and could exhibit some time dependence; it is intriguing to find that our best fit with LWO to the seasonal $^{37}$Cl data (using results cited in Ref. [23]) is actually better (lower $\chi^2$) than a fit to constant $R_{\text{Cl}}$ with no time dependence. At present this is just an interesting hint, not a statistically significant result. The $^{71}$Ga and BOREXINO signals, however, contain larger components from the $^7$Be line and could provide better evidence. Typical LWO solutions with $\delta m^2$ of order $5 \times 10^{-11}$, $1 \times 10^{-10}$ and $2.5 \times 10^{-10}$ eV$^2$ have differences between maximal and minimal six-month $^{71}$Ga count rate of up to 8, 17 and 29 SNU, respectively, due to the variation in the Earth-Sun distance. Ultimately, the statistical uncertainty in a six-month gallium measurement may be reduced to 7 SNU, so these variations may be detectable in $^{71}$Ga for solutions with larger $\delta m^2$. In the BOREXINO experiment the count rate is much higher; the statistical uncertainty in the monthly measurement of $R$ may be as low as 0.04. The ranges of differences between maximal and minimal monthly measurements of $R$ in BOREXINO are 0.02–0.24, 0.09–0.45 and 0.39–0.66, respectively, for LWO solutions in the three aforementioned $\delta m^2$ regions. Hence, there is a strong likelihood that the time dependence could be observed in BOREXINO in a LWO scenario.

The Sudbury Neutrino Observatory (SNO) experiment [24] cannot detect $^7$Be neutrinos and will therefore have little time dependence, but will be able to test a second distinctive property of LWO, namely an oscillatory modulation of the $^8$B neutrino spectrum. This property follows immediately from the expression for $P(\nu_e \to \nu_e)$, that oscillates versus $E_{\nu}$ when measured at (approximately) constant $L$. SNO will obtain a determination of the high-energy $^8$B neutrino spectrum through its measurement of charged-current $\nu_e d \to ppe^- \text{scattering}$. Here the neutrino energy will be measured directly, not averaged (as in $^{37}$Cl capture) nor smeared by the recoil electron distribution (as in $\nu-e$ scattering). $P(\nu_e \to \nu_e)$ is given by the ratio of the observed $^8$B spectrum to the
calculated spectrum; the normalization of the latter may be affected by the solar model but the shape is not. Figure 3 illustrates the dependence of $P(\nu_e \rightarrow \nu_e)$ on $E_\nu$ for our best-fit LWO solution (including an average over the varying Earth-Sun distance); we see that a clear oscillation minimum is predicted in the energy range above 5 MeV, the practical threshold for SNO. This behavior is distinguishable from that of two MSW solutions, also shown. If this $^8\text{B}$ spectrum modulation or the $^7\text{Be}$ time dependence were detected, they would provide the first case(s) in which a resolved neutrino oscillation had been seen.

SNO will also detect neutral-current $\nu_\alpha d \rightarrow \nu_\alpha pn$ scattering, which will help determine if oscillations are occurring to sterile neutrinos. For example, in a sterile neutrino oscillation scenario both the CC and NC ranges would be suppressed (to perhaps $R \approx 0.4$), while for $\nu_e-\nu_\alpha$ oscillations only the CC rate would be suppressed.

We conclude the following:
(a) The LWO hypothesis with two-neutrino mixing can comfortably account for the present $^{37}\text{Cl}$, Kamiokande and $^{71}\text{Ga}$ data. There are discrete regions of fit as shown, for either active or sterile neutrino mixing.
(b) Time-averaged BOREXINO measurements may not cleanly discriminate between LWO and MSW solutions, since their predictions overlap considerably.
(c) A very distinctive signature of LWO solutions, however, is the seasonal time-dependence of the $^7\text{Be}$ line. There is at present no more than an intriguing hint in the $^{37}\text{Cl}$ data, but future BOREXINO measurements would probably be able to detect this seasonal dependence.
(d) Another distinctive LWO signature is the oscillatory modulation of the $^8\text{B}$ spectrum shape, which should be tested at SNO. More precise data of all kinds should also restrict the options in the future.
(e) Measurements of NC scattering in SNO may possibly discriminate between active-neutrino and sterile-neutrino mixing options.

Up until now we have discussed oscillations between two neutrino species, but oscillations among three neutrino flavors are another possibility. Although the maximal three-neutrino mixing case (which predicts $R_{\text{Kam}} = 0.43$ and a $^{71}\text{Ga}$ rate of 44 SNU) is clearly disfavored by the
new Kamiokande III and GALLEX data, many other scenarios with mass-squared difference scales in the $\delta m^2 \sim 10^{-10} \text{eV}^2$ range can comfortably account for these results [11,17,18]. The allowed range of BOREXINO predictions is larger, and the three-neutrino solutions have the characteristic seasonal variations and oscillatory modulation of two-neutrino LWO.
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FIGURES

FIG. 1. LWO solutions to Homestake plus Kamiokande data are shown as shaded regions in the \((\sin^2 2\theta, \delta m^2)\) plane, for (a) \(\nu_e - \nu_\alpha\) active neutrino mixing \((\alpha = \mu \text{ or } \tau)\) and (b) \(\nu_e - \nu_X\) sterile neutrino mixing. Solid curves denote iso-SNU contours of the predicted \(^{71}\text{Ga}\) capture rate in each case.

FIG. 2. LWO solutions to Homestake plus Kamiokande plus GALLEX data are shown as shaded regions in the \((\sin^2 2\theta, \delta m^2)\) plane, for (a) \(\nu_e - \nu_\alpha\) mixing \((\alpha = \mu \text{ or } \tau)\) and (b) \(\nu_e - \nu_X\) mixing. Solid curves are contours of the suppression ratio \(R\) for the time-averaged \(\nu-e\) scattering signal in the BOREXINO detector, in the band \(0.25 < T_e < 0.66\text{keV}\).

FIG. 3. Electron-neutrino survival probability \(P(\nu_e \rightarrow \nu_e)\) is shown versus neutrino energy \(E_\nu\) for the best-fit \(\nu_e - \nu_\alpha\) LWO solution \((\delta m^2 = 6.4 \times 10^{-11}\text{eV}^2\) and \(\sin^2 2\theta = 0.83\), solid curve\) and solutions typifying the two MSW regions of fit: \(\delta m^2 = 5.0 \times 10^{-6}\text{eV}^2\), \(\sin^2 2\theta = 0.008\) (dashed curve) and \(\delta m^2 = 1.0 \times 10^{-5}\text{eV}^2\), \(\sin^2 2\theta = 0.8\) (dotted curve).