Testing the solar LMA region with KamLAND data

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Abstract: In this paper we investigate the potential of 1 and 3 kiloTon-years (kTy) of KamLAND data to further constrain the $\Delta m^2$ and $\tan^2 \theta$ values allowed by the post-SNO NC global solar data. We find that although an energy integrated oscillation to no oscillation event-rate ratio in the range $\sim 0.3 - 0.8$ observed in KamLAND can provide support for the Large-Mixing Angle (LMA) solution, sensitive determination of the oscillation parameters will have to wait until the spectrum data is made available. We study the extent, dependence and characteristics of this sensitivity in and around the LMA region. Our analysis with 3 kTy simulated spectra shows that KamLAND spectrum data by itself can constrain $\Delta m^2$ with a high precision if the simulation point lies around the LMA best-fit from global solar analysis. For spectra generated at lower values of $\tan^2 \theta$ or higher values of $\Delta m^2$, multiple regions become allowed indicating a significantly reduced reconstruction efficiency if the true spectrum corresponds to these choices. Combining the spectrum with global solar data tightens the constraints on allowed values of $\tan^2 \theta$ and wipes away much of the high $\Delta m^2$ and low $\tan^2 \theta$ regions resulting in a high precision in determination of the oscillation parameters in almost all of the LMA region except that corresponding to values of $\Delta m^2 \gtrsim 2 \times 10^{-4}$ eV$^2$. We show that the incorporation of the CHOOZ data in the analysis reduces the size of the high $\Delta m^2$ regions to some extent.

Keywords: Solar and Atmospheric Neutrinos, Neutrino Physics.
1. Introduction

The Sudbury Neutrino Observatory (SNO) charged current (CC) and neutral current (NC) data on the measurement of solar neutrino flux has provided strong evidence for neutrino flavour conversion [1, 2]. In conjunction with Super-Kamiokande (SK) results [3], it establishes the presence of $\nu_\mu/\nu_\tau$ flavour in the solar $\nu_e$ flux at 5.5$\sigma$ level. The SNO and SK results together with the data from the radiochemical experiments Cl [4] and Ga [5] single out the LMA solution based on MSW resonant matter conversion as the most probable solution of the solar neutrino puzzle [6]-[16]. In [8], for instance, this solution is characterized by best fit values of $\tan^2 \theta = 0.41$, $\Delta m^2 = 6.06 \times 10^{-5}$eV$^2$ for the neutrino mixing parameters.

Expectations are high that confirmation in favour of the LMA solution, using terrestrial neutrino sources, will come from the KamLAND experiment in Japan [17]. The uniqueness of KamLAND lies in its sensitivity to masses and mixing angles lying in the LMA region. With the accumulated statistics of about three years of data taking, KamLAND has the potential to not only confirm the LMA solution but also to precisely determine $\tan^2 \theta$ and $\Delta m^2$ if they lie in the LMA region except for values of $\Delta m^2 \gtrsim 2 \times 10^{-4}$ eV$^2$ [18–24]. KamLAND is expected to announce their first data shortly 1.

In this paper, we consider a broader time-frame than will be spanned by the first results, and obtain projected results and conclusions that should be forthcoming from a 1 and 3 kTy exposure. We do a detailed analysis of the KamLAND and

1At the PANIC 2002 conference [25] sensitivity plots of 150 days data with a visible energy threshold of 2.6 MeV were shown. We use this threshold in our calculations.
available global solar data with a few representative values of total integrated rate (in the form of oscillation to no oscillation ratio) for the former. We determine the allowed areas in the $\Delta m^2$-$\tan^2 \theta$ plane from this analysis and in the process show that an observed KamLAND total rate as predicted by the solar best-fit can only loosely constrain the LMA allowed zone. We also simulate the 3 year KamLAND spectrum at several sample $\Delta m^2$ and $\tan^2 \theta$ values and attempt to delineate in detail the limits of sensitivity for KamLAND over a 3 kTy period, by itself as well as in conjunction with available solar neutrino data. We study the dependence of the reconstituted parameter regions on the sample values of $\Delta m^2$ and $\tan^2 \theta$ chosen and demonstrate that for spectrum simulated at points inside the LMA region the accuracy of reconstruction is quite high, leading to an excellent precision in determination of oscillation parameters, excepting for $\Delta m^2 \gtrsim 2 \times 10^{-4}$ eV$^2$ for which the KamLAND spectrum is flat and gives multiple allowed regions. Multiple regions also appear for points outside the LMA zone for which $\tan^2 \theta$ is low demonstrating that KamLAND spectrum is fine tuned to test the LMA region. Finally we include the results from the CHOOZ [26] reactor experiment and do a combined analysis with global solar, CHOOZ and 3 kTy KamLAND spectral data. The inclusion of the CHOOZ data is seen to reduce the ambiguity in the high $\Delta m^2$ region to some extent. Our analysis, besides including the SNO NC data, incorporates the updated KamLAND energy resolution and systematics [25].

Section 2 describes the salient features of the KamLAND detector, and the expected $\bar{\nu}_e$ reactor flux to which it is sensitive. In Section 3 we discuss the analysis procedure and results. Section 4 summarises our conclusions.

2. The KamLAND detector, the reactor flux of Electron Antineutrinos and the Event Rate

KamLAND [17] is a 1 kton liquid scintillator neutrino detector located at the earlier Kamiokande site in the Kamioka mine in Japan. It measures the $\bar{\nu}_e$ flux from 16 Japanese nuclear power reactors whose distances range from 80 km to 800 km. The bulk ($\approx 78\%$) of the measured flux, however, is from reactors which are at distances between 140 km to 215 km from the detector.

The $\bar{\nu}_e$s are detected via the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Both the scintillation emitted by the positron as it moves through the detection medium, and its subsequent annihilation with an electron are recorded. The annihilation, with its time co-relation to the $\gamma$-ray from the capture of the neutron that is produced in the reaction in conjunction with the positron, provides a strong and largely back-ground free mode of identification. The total visible energy ($E_{\text{vis}}$) corresponds to $E_{e^+} + m_e$, where $E_{e^+}$ is the total energy of the positron and $m_e$ the electron mass. The total positron energy is related to the incoming antineutrino energy $E_\nu$ through the relation, $E_{e^+} =$
Table 1: Fitted Parameters $a_k, k = 0, 1, 2$ for the reactor neutrino spectrum. The last row shows the energy released for each isotope per fission.

| Isotope | $^{235}\text{U}$ | $^{239}\text{Pu}$ | $^{238}\text{U}$ | $^{241}\text{Pu}$ |
|---------|-----------------|-----------------|-----------------|-----------------|
| $a_0$   | 0.870           | 0.896           | 0.976           | 0.793           |
| $a_1$   | -0.160          | -0.239          | -0.162          | -0.080          |
| $a_2$   | -0.0910         | -0.0981         | -0.0790         | -0.1085         |
| $\epsilon_j$ (MeV) | 201.7 | 205.0 | 210.0 | 212.4 |

$E_\nu - (m_n - m_p)$, where $m_n - m_p = 1.293$ MeV is the neutron–proton mass difference. Here we neglect the recoil of the daughter neutron. KamLAND’s energy resolution for this reaction is $\sigma(E)/E = 7.5%/\sqrt{E}$, $E$ in MeV [25].

The neutrino spectrum from the fission of a particular isotope, $j$ is conveniently parametrizable [19, 27] (in units of MeV$^{-1}$ per fission) as

$$dN_j^i/dE_\nu = \exp(a_0 + a_1E_\nu + a_2E_\nu^2). \quad (2.1)$$

Here $j = 1, 2, 3, 4$, corresponding to the 4 isotopes $^{235}\text{U}, ^{239}\text{Pu}, ^{238}\text{U}, ^{241}\text{Pu}$ which constitute the fuel. The fitted values of the $a_k's$ in the equation above are reproduced for completeness from [19, 27] in Table 1.

In addition, each isotope has a characteristic energy released per fission, $\epsilon_j$. These are also reproduced from [27] in Table 1.

Table 2 (from [17]) gives the distances of the various reactors from the Kamioka mine which houses KamLAND, along with the maximum thermal power $N_{\text{max}}^i$ (in Giga-watts) of each $i$, the reactor index, which runs from 1 − 16. Also, we note that in principle, the power of each reactor varies over the year depending on demand, fuel composition, re-fuelling times etc. This dependance is averaged over, and we assume that each reactor is in the running mode at maximum output 80% of the time. Using the above data, one may then write an expression for the spectrum from a given reactor $i$ as,

$$S_i = \sum_j f_j^i N_{\text{max}}^i (0.8) \sum_k f_k^i \epsilon_k dN_j^i/dE_\nu. \quad (2.2)$$

Here $f_j^i$ is the fractional abundance of isotope $j$ in reactor $i$ at a given time. The time dependance is again averaged over, and for all the reactors we use for the abundance the values, 53.8% for $^{235}\text{U}$, 32.8% for $^{239}\text{Pu}$, 7.8% for $^{238}\text{U}$, and 5.6% for $^{241}\text{Pu}$, as in [18]. Convenient units for $S_i$ are MeV$^{-1}$sec$^{-1}$, obtained by converting the power in Giga-watts into Mev per sec by multiplying by the factor $6.24 \times 10^{24}$.

The other quantities needed to determine the event rate are the cross-section, the survival probability for anti-neutrinos and the number of free proton targets in
Table 2: Reactor distances and power outputs

| Reactor Site | Distance $d_i$ (km) | Power $N_{max}^i$ (Giga-watts) |
|--------------|---------------------|-------------------------------|
| Kashiwazaki  | 160                 | 24.6                          |
| Ohi          | 180                 | 13.7                          |
| Takahama     | 191                 | 10.2                          |
| Hamaoka      | 213                 | 10.6                          |
| Tsuruga      | 139                 | 4.5                           |
| Shiga        | 81                  | 1.6                           |
| Mihama       | 145                 | 4.9                           |
| Fukushima-1  | 344                 | 14.2                          |
| Fukushima-2  | 344                 | 13.2                          |
| Tokai-II     | 295                 | 3.3                           |
| Shimane      | 414                 | 3.8                           |
| Ikata        | 561                 | 6.0                           |
| Genkai       | 755                 | 6.7                           |
| Onagawa      | 430                 | 4.1                           |
| Tomari       | 784                 | 3.3                           |
| Sendai       | 824                 | 5.3                           |

the scintillator. The cross-section is given by

$$\sigma(E_\nu) = \frac{2\pi^2}{m_e^5 f \tau_n} p_{e+} E_{e+}.$$  \hspace{1cm} (2.3)

Here $f = 1.69$ is the integrated Fermi function for neutron $\beta$-decay, $m_e$ is the positron mass, $E_{e+}$ is the positron energy, $p_{e+}$ is the positron momentum and $\tau_n = 886.7$ secs is the neutron lifetime. The two-generation survival probability for the antineutrinos from each of the reactors $i$ is given by

$$P_i(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 d_i}{E_\nu} \right)$$  \hspace{1cm} (2.4)

where $d_i$ is the distance of reactor $i$ to KamLAND in $km$, $E_\nu$ is in GeV and $\Delta m^2$ is in eV$^2$. Thus the total observed event-rate in KamLAND is given by $N_{KL}$ in sec$^{-1}$,

$$N_{KL} = \int dE_\nu \sigma(E_\nu) N_p \sum_i P_i(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) \frac{S_i P_i(\bar{\nu}_e \leftrightarrow \bar{\nu}_e)}{4\pi d_i^2}$$  \hspace{1cm} (2.5)

where $N_p$ is the number of free protons in the fiducial volume of the detector. For 1 kton volume of the scintillator, which is a mixture of isoparaffin and pseudocumene
Figure 1: The isorate lines for the KamLAND detector in the $\Delta m^2 - \tan^2 \theta$ plane. Also shown by solid line is the $3\sigma$ allowed area from the global analysis of the solar neutrino data. The best-fit solution for the solar data is marked.

in a ratio which yields 1.87 free protons per carbon atom [17], we get $N_p = 8.1 \times 10^{31}$. The ratio of the observed event-rate to the expected rate in KamLAND is defined as

$$R_{KL} = \frac{N_{KL}}{N_{KL}^0}$$

where $N_{KL}^0$ is the expected event-rate in KamLAND given by Eq.(2.5) with $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1$.

3. Analysis and Results

In Figure 1 we show the lines of constant KamLAND rate $R_{KL}$ in the $\Delta m^2 - \tan^2 \theta$ plane. The best-fit point from global solar neutrino analysis and the corresponding $3\sigma$ LMA contour (dashed line) is also shown. We note that the best-fit point [7,8] of the global solar neutrino data predicts a KamLAND rate of 0.65, while the $3\sigma$ range predicted by the LMA solution lies approximately between the KamLAND isorates corresponding to 0.26 and 0.73. We also note that for any observed $R_{KL}$, including the best-fit prediction 0.65, the isorate curve spans values of the $\Delta m^2 - \tan^2 \theta$ both within and well outside the $3\sigma$ solar contour. spectrum. A particular observed $R_{KL}$ may correspond to a wide range of KamLAND spectra. The reverse, of course, is not true since an observed KamLAND spectrum singles out a unique rate (within errors).
We first do a statistical analysis with the KamLAND rate alone. For the rate we define the $\chi^2$ as

$$\chi^2_{KL} = \frac{(R_{KL}^{\text{exp}} - R_{KL}^{\text{theory}})^2}{\sigma^2}$$

(3.1)

where $\sigma = \sqrt{\sigma_{\text{syst}}^2 + \sigma_{\text{stat}}^2}$, $\sigma_{\text{syst}}$ and $\sigma_{\text{stat}}$ being the total systematic and statistical error in the KamLAND data respectively. We take 6.1% systematic uncertainty along with $\sqrt{N_{KL}}$ statistical errors corresponding to 1 kTy of data. To eliminate the geophysical background we take a visible energy threshold of 2.6 MeV, and adopt an energy resolution of $\sigma(E)/E = 7.5%/\sqrt{E}$ ($E$ in MeV) [25]. We get 637 expected events in KamLAND for 1 kTy of data for the case of no oscillations. This is in excellent agreement with the expected event rates calculated by the KamLAND collaboration [25] \(^2\).

In Figure 2 we show the C.L. contours in the $\Delta m^2 - \tan^2 \theta$ plane for four different anticipated KamLAND rates of 0.3, 0.6, 0.65 and 0.8 for 1 kTy of data. Also shown by dashed lines in the panels are the 3$\sigma$ contour for the global solar neutrino data. The maximum overlap between the KamLAND and solar 3$\sigma$ contours are for the $R_{KL} = 0.6$.

\(^2\)The first results due to be announced by KamLAND would in all probability correspond to 150 days of data in 600 tons of fiducial volume. For this we expect only 157 events for the case of no oscillations. For our analysis however we have used 1 kTy and 3 KTy exposures to bring out the full potential of the detector.
Figure 3: $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ ($\chi^2 = \chi^2_\odot + \chi^2_{KL}$) vs the KamLAND rate $R_{KL}$ for the LMA and LOW solutions. The dashed line indicates the 99.73% C.L. limit.

For a more complete statistical study, we next do a combined analysis of global solar data and the anticipated KamLAND rates for 1 kTy exposure. We use a combined $\chi^2$ function defined as

$$\chi^2 = \chi^2_\odot + \chi^2_{KL}$$  \hspace{1cm} (3.2)

For the solar ($\chi^2_\odot$), we use the data on total rate from the Cl experiment, the combined rate from the Ga experiments (SAGE+GALLEX+GNO), the 1496 day data on the SK zenith angle energy spectrum and the combined SNO day-night spectrum. We define the $\chi^2$ function in the “covariance” approach as

$$\chi^2_\odot = \sum_{i,j=1}^N (R_i^{\text{expt}} - R_i^{\text{theory}})(\sigma_{ij}^2)^{-1}(R_j^{\text{expt}} - R_j^{\text{theory}})$$  \hspace{1cm} (3.3)

where $R_i$ are the solar data points, $N$ is the number of data points (80 in our case) and $(\sigma_{ij}^2)^{-1}$ is the inverse of the covariance matrix, containing the squares of the correlated and uncorrelated experimental and theoretical errors. For further details of our solar analysis we refer the reader to [8, 9].

In Figure 3 we have plotted the $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$, with $\chi^2$ defined in Eq. (3.2) vs the ratio of oscillation to no oscillation events $R_{KL}$, keeping the parameters $\Delta m^2$ and $\tan^2 \theta$ free in the LMA and LOW regions. The minimum $\chi^2$ in the LMA region comes for a KamLAND ratio of 0.65 at the solar best-fit. At this value $\chi^2_{\min} = \chi^2_{\odot; \text{min}}(LMA)$. At 99.73% C.L. the values of allowed KamLAND rates in the
Figure 4: The 90%, 95%, 99% and 99.73% C.L. contours in the LMA region for solar+KamLAND rates analysis. The different panels are for different anticipated observed rates in KamLAND. The dashed line shows the 3σ only solar contour.

LMA region are 0.26 – 0.88. Beyond $R_{KL} = 0.9$ the combined $\chi^2$ for LOW is seen to be lower than that for LMA. Thus from this plot we infer that the LMA solution remains allowed even if the observed KamLAND rate is as low as 0.26 or as high as 0.88. We have checked that this allowed range is not reduced significantly even for 5 kTy of KamLAND data on total rates, since the systematic error of 6.1% is large enough to override the reduction in the statistical error.

In Figure 4 we draw the 90%, 95%, 99% and 99.73% C.L. allowed area in the LMA region from a combined solar+KamLAND rate analysis. Superimposed on that we show the 3σ allowed area from solar data alone. We draw the global solar+KamLAND contours for KamLAND rates of 0.3, 0.6, 0.65 and 0.8. In this set of figures the maximum allowed area is is seen to come for an observed KamLAND rate of 0.6. As we move towards lower or higher KamLAND rates the combined allowed area decreases.

In Figure 5 we show the allowed area in the LOW region from a solar+KamLAND rate analysis. Also shown in the figure is the 3σ allowed region in LOW from global solar data. For $R_{KL} = 1.0$ the 3σ allowed area from solar+KamLAND rate is seen to completely overlap with that from only solar. This is not surprising, since for the very low $\Delta m^2$ involved in LOW, there is no predicted depletion of the $\bar{\nu}_e$ flux in KamLAND and hence an observed $R_{KL} = 1$ would imply $\chi^2_{KL} = 0$. However for lower observed rates in KamLAND, LOW starts to get disfavored as seen in the panel for $R_{KL} = 0.9$ and below this value it completely disappears.
Figure 5: The 99.73% C.L. contour (solid line) in the LOW region for \( R_{KL} = 0.9 \) and \( R_{KL} = 1.0 \). The 3σ solar contour is shown by the dashed line.

Next, our aim is to see how far the allowed areas can be constrained with the inclusion of KamLAND spectrum data. We choose some representative values of \( \Delta m^2 \) and \( \tan^2 \theta \) allowed by KamLAND rate in the range of 0.3–0.8 and simulate the spectrum at these points for 3 kTy of data, using a randomizing procedure to incorporate fluctuations. We use these simulated spectra in a \( \chi^2 \) analysis and reconstruct the allowed regions in the \( \Delta m^2 - \tan^2 \theta \) parameter space. The \( \chi^2 \) for the KamLAND spectrum is defined as

\[
\chi^2_{KL\text{spec}} = \sum_{i,j} \left( S^{\text{expt}}_{KL,i} - S^{\text{theory}}_{KL,i} \right) (\sigma_{ij}^{KL})^{-1} \left( S^{\text{expt}}_{KL,j} - S^{\text{theory}}_{KL,j} \right)
\]

where the sum is over the KamLAND spectral bins and \( (\sigma_{ij}^{KL}) \) is the correlation error matrix for the KamLAND spectrum. We assume that the systematic errors for all the bins is 6.1% and is fully correlated between the bins. The actual binning of the data will be known after KamLAND releases its spectrum data. However for the purpose of illustration we choose bins of 0.5 MeV width from 2.6 MeV to 7.6 MeV visible energy.

Figure 6 shows the reconstituted C.L. allowed contours in parameter space from a \( \chi^2 \) analysis using the simulated KamLAND spectrum alone. Marked by black dots are the points at which the spectra have been simulated. Each panel in this set of plots serves to identify regions with similar spectra in and around the vicinity of the LMA region and demonstrates the constraining capabilities of the KamLAND spectral data. The panel 4 is for the spectrum simulated at the best-fit solar point,
Figure 6: The 90%, 95%, 99% and 99.73% C.L. contours for the KamLAND spectrum analysis alone. The different panels are for the simulated spectrum at different fixed values of $\Delta m^2$ and $\tan^2 \theta$ shown by bold dots. The dashed line shows the 3σ only solar contour, drawn here for reference purposes.

$\Delta m^2 = 6.06 \times 10^{-5} \text{ eV}^2$ and $\tan^2 \theta = 41$. We see that for $\Delta m^2$ and $\tan^2 \theta$ around the solar best-fit the (panels 3, 4 and 6) the sensitivity in $\Delta m^2$ is within $\sim \pm 6\%$ at 3σ range of the simulation point indicating a very high reconstruction efficiency. Panel 6 shows that the reconstruction efficiency in $\tan^2 \theta$ improves if we go slightly below the best-fit $\Delta m^2$ obtained from global solar data. Tighter constraints on $\Delta m^2$ are also associated with higher values of $\tan^2 \theta$ (cf. panel 3 and 4, 6 and 8). However as we choose higher $\Delta m^2$ values within the allowed LMA parameter space, the expected flattening of the spectrum leads to increased fuzziness and large allowed regions (cf. panels 1 and 5). Also note the appearance of low $\Delta m^2$ and low $\theta$ allowed regions away from the original point, when the true values of $\Delta m^2$ are higher ($\geq 10^{-4} \text{ eV}^2$) and/or that of $\tan^2 \theta$ are lower. Ambiguity increases dramatically as $\tan^2 \theta$ is pushed to lower values, outside the LMA region for instance, as shown in panel 8.

Figure 6 shows the simulated spectrum with $\pm 1\sigma$ errorbars at the $\Delta m^2$ and $\tan^2 \theta$ corresponding to each of the panels in Figure 6. We have explicitly shown the relevant $\Delta m^2$ and $\tan^2 \theta$ values in all the panels. In general, tighter constraints in the Figure 6 are associated with spectra which are significantly different from flat. We note that the spectral shape for the last two panels are almost identical and statistically indistinguishable. Both correspond to almost no spectral distortion.
Figure 7: The simulated KamLAND spectrum for the different sets of $\Delta m^2$ and $\tan^2 \theta$ corresponding to Figure 6.

The spectra tend to be flatter as $\Delta m^2$ increases and/or $\tan^2 \theta$ decreases. Flatness of the spectrum at low values of $\tan^2 \theta$ is due to the diminished energy dependence resulting from a small oscillatory term in the survival probability while for higher values of $\Delta m^2$ it is a consequence of the averaging of the oscillatory term due to rapid oscillations.

In Figure 8 we show the C.L. allowed regions from a combined analysis of the global solar and the 3 kTy KamLAND simulated spectrum data. The KamLAND spectra, as before, are simulated at the points shown by bold dots in the figure. Also superimposed is the 3$\sigma$ only solar contour. The allowed areas are seen to be tightly constrained for $\Delta m^2$ within the LMA region, thanks to the high sensitivity of the KamLAND spectrum to distortions driven by this parameter. If we compare Figure 8 to Figure 6, we also note that the contours get more constricted in $\tan^2 \theta$ with the inclusion of the global solar data. Thus the neutrino oscillation parameters within the LMA can be determined with unprecedented accuracy if KamLAND observes spectral distortions. Many of the fuzzy regions outside the LMA, both at high and low $\Delta m^2$ and low $\tan^2 \theta$, allowed by only KamLAND spectrum data (cf. panel 1 of Figure 6) disappear with the inclusion of the solar data. However for the spectra simulated at higher values of $\Delta m^2$ ($\geq 2.0 \times 10^{-4} \text{ eV}^2$) and/or lower values of $\theta$ outside LMA region (panels 5, 7 and 8), large “allowed” regions still remain specially at higher $\Delta m^2$ values. For these high $\Delta m^2$ values the contribution from $\chi_{KL}^2$ falls very sharply.
Figure 8: The 90%, 95%, 99% and 99.73% C.L. contours for the combined solar+KamLAND spectrum analysis. The different panels are for the simulated spectrum at values of $\Delta m^2$ and $\tan^2 \theta$ of the corresponding panels of Figures 6 and 7. The dashed line shows the 3$\sigma$ only solar contour.

whereas the $\chi^2_\odot$ increases a little bit and these areas become allowed. We note that in these regions the compatibility between the Ga and other solar rates as well as the flat SK spectrum favours a $^8B$ flux normalisation factor, $f_B \sim 0.8$ and nearly maximal mixing (including a part of the dark region).

In order to constrain the high $\Delta m^2$ zones that remain allowed even after including the KamLAND and global solar neutrino data, we introduce the CHOOZ reactor data. We define the global $\chi^2$ as

$$\chi^2_{\text{global}} = \chi^2_\odot + \chi^2_{KL\text{spec}} + \chi^2_{\text{chooz}}$$

where the $\chi^2_{\text{chooz}}$ is defined as in [28]. In Figure 8 we show the allowed areas in the parameter space from the combined analysis involving the CHOOZ data along with the global solar data and 3 kTy KamLAND spectrum. The panels i (i=5,7,8) labelled in this figure correspond to the panels i in Figures 6 and 8. We find that some of the high $\Delta m^2$ regions which we were allowed in Figure 8 gets disfavored by CHOOZ.

4. Conclusions

We have studied the capability of the KamLAND experiment to test the LMA so-
Figure 9: The combined CHOOZ+solar+KamLAND C.L. contours. The different panels are for the simulated spectrum at different fixed values of $\Delta m^2$ and $\tan^2 \theta$ shown by bold dots. The numbering of the panels correspond to those of Figure 8. The dashed line shows the $3\sigma$ only solar contour.

Solution to the solar neutrino problem, which stands out today as the most probable resolution of this 30 year old puzzle. We find, that an energy integrated oscillation to no oscillation ratio in the range 0.3 - 0.8 in KamLAND will provide support for the LMA solution. Additionally, we perform a combined analysis of solar data and KamLAND total rate using a few representative values in the above range. We find that if we choose a total KamLAND rate around that predicted by points near the LMA best-fit the allowed range of parameters is only loosely constrained. However for a KamLAND rate away from that predicted by the LMA best-fit the combined allowed areas are significantly reduced due to a mismatch between the global solar and KamLAND data.

Precise determination of the oscillation parameters is possible with the KamLAND spectrum data. To explore its sensitivity, we simulate the spectrum in and around the LMA region for an exposure of 3 kTy. We find that for points around the LMA best-fit the spectral distortion that can be observed by KamLAND is maximum and consequently the KamLAND spectrum data by itself can constrain $\Delta m^2$ very sharply within $\sim \pm 6\%$. Inclusion of the solar data in the analysis has the effect of further constraining the allowed range of $\tan^2 \theta$. Our analysis shows that $\tan^2 \theta$ is most sharply constrained if the spectrum is simulated at a $\Delta m^2$ slightly lower than
the LMA best-fit.

For spectra generated at higher values of $\Delta m^2$ inside the LMA region and/or lower values of $\tan^2 \theta$ outside the LMA region the combined analysis gives multiple allowed regions, some of them far removed from the original simulation point. In a sense they demonstrate that the KamLAND spectrum data is fine tuned to precisely determine the oscillation parameters in the LMA region excepting for $\Delta m^2 \gtrsim 2 \times 10^{-4}$ eV$^2$. The inclusion of the CHOOZ data in the analysis can constrain the high $\Delta m^2$ regions to some extent. The regions that still remain allowed can be constrained by reactor experiments with shorter baselines [29].

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