Neutrino Physics around MeV Energies
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We present a brief informative overview of a broad range of subjects, the solar, the reactor, the geo and the supernova neutrinos (but without excluding possible biases), the topics which consist of the session “Neutrino Physics around MeV Energies” in NOW2006. Contrary to the naive expectation, the field is found to be very active in improving the performance of existing detectors, and in preparation for the development coming in the near future. The former includes excellent performance of SNO \textsuperscript{3}He detector, successful reconstruction of SK III, and KamLAND’s new “4\pi” calibration. The next data release from these experiments will be very exciting. The latter includes effort for lowering threshold in SK III, KamLAND’s purification by which geo-neutrino observation becomes much cleaner, and the forthcoming \textsuperscript{7}Be neutrino measurement by BOREXINO and KamLAND. Possible detection of relic supernova neutrinos and non-zero effect of \(\theta_{13}\) would bring us great excitement. Furthermore, improved new measurement of heavy element abundance in the solar atmosphere resulted in a solar model with much lower CNO \(\nu\) flux and with disagreement with helioseismology, thereby bringing us a new solar puzzle.

1. Solar neutrinos

The past and the ongoing solar neutrino experiments cover a wide variety of interesting aspects of solar neutrinos \cite{1}. Davis’ chlorine experiment which pioneered the solar neutrino search has been continuing for more than 30 years. Gallium experiments have a sensitivity on the most elemental pp neutrinos. Super-Kamiokande (SK) is performing precise measurement of mainly \textsuperscript{8}B neutrinos with highest statistics. SNO has provided an evidence for neutrino flavor transformation with CC/NC measurement \cite{2}.

Missing piece from the experimental side is a realtime spectrum measurement at energies below 5 MeV. Individually measured fluxes of pp, \textsuperscript{7}Be and pep neutrinos will be the key to complete the verification of the standard solar model (SSM). A measurement of CNO cycle neutrinos would be a realization of Davis’ initial dream and it will contribute to construct the stellar evolution model. Along these motivations, there are two forthcoming experiments: KamLAND solar phase \cite{3} and BOREXINO \cite{4}. They will start by observing \textsuperscript{7}Be neutrinos which have high signal rate and the characteristic spectrum edge. Also, pep/CNO neutrinos are seen within their scopes but they require special treatment on \textsuperscript{11}C spallation background. This background is more serious for KamLAND which is placed in shallower site but tagging the associated neutrons (~95\% BR) will drastically improve the situation. A new electronics designed for maximizing the rejection efficiency is being developed. Proposed SNO\textsuperscript{+} with liquid scintillator will have much better sensitivity to these neutrinos thanks to its size and depth. The realtime measurement of pp neutrino is very challenging. It requires very powerful background rejection method/apparatus such as delayed coincidence or non-carbonic ultra pure detector. LENS \cite{5} revived an idea of indium loaded liquid scintillator (3 fold delayed coincidence) with sophisticated fine segmentation techniques.

Measurement of expected upturn in low energy \textsuperscript{8}B neutrino spectrum will possibly provide the still missing experimental proof of the LMA solution in the solar neutrino data. Because the flux is small, it requires a very big detector. The largest solar neutrino detector, SK-III which has been restarted with full PMT installation in July 2006, is aiming at the measurement \cite{6}.

From the theory side or the viewpoint of solar model building, recent progresses on the im-
Table 1
Predicted solar neutrino fluxes from seven solar models. Taken from [9]. The table presents the predicted fluxes, in units of $10^{10}(pp)$, $10^9(7\text{Be})$, $10^8(\text{pep,}^{13}\text{N},^{15}\text{O})$, $10^6(8\text{B},^{17}\text{F})$, and $10^4(\text{hep})\text{ cm}^{-2}\text{s}^{-1}$ for the seven different solar models calculated in [9]. The last two models utilize the new metal abundance data.

<table>
<thead>
<tr>
<th>Model</th>
<th>pp</th>
<th>pep</th>
<th>hep</th>
<th>$^7\text{Be}$</th>
<th>$^8\text{B}$</th>
<th>$^{13}\text{N}$</th>
<th>$^{15}\text{O}$</th>
<th>$^{17}\text{F}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP04(Yale)</td>
<td>5.94</td>
<td>1.40</td>
<td>7.88</td>
<td>4.86</td>
<td>5.79</td>
<td>5.71</td>
<td>5.03</td>
<td>5.91</td>
</tr>
<tr>
<td>BP04(Garching)</td>
<td>5.94</td>
<td>1.41</td>
<td>7.88</td>
<td>4.84</td>
<td>5.74</td>
<td>5.70</td>
<td>4.98</td>
<td>5.87</td>
</tr>
<tr>
<td>BS04</td>
<td>5.94</td>
<td>1.40</td>
<td>7.86</td>
<td>4.88</td>
<td>5.87</td>
<td>5.62</td>
<td>4.90</td>
<td>6.01</td>
</tr>
<tr>
<td>BS05($^{14}\text{N}$)</td>
<td>5.99</td>
<td>1.42</td>
<td>7.91</td>
<td>4.89</td>
<td>5.83</td>
<td>3.11</td>
<td>2.38</td>
<td>5.97</td>
</tr>
<tr>
<td>BS05(OP)</td>
<td>5.99</td>
<td>1.42</td>
<td>7.93</td>
<td>4.84</td>
<td>5.69</td>
<td>3.07</td>
<td>2.33</td>
<td>5.84</td>
</tr>
<tr>
<td>BS05(AGS,OP)</td>
<td>6.06</td>
<td>1.45</td>
<td>8.25</td>
<td>4.34</td>
<td>4.51</td>
<td>2.01</td>
<td>1.45</td>
<td>3.25</td>
</tr>
<tr>
<td>BS05(AGS,OPAL)</td>
<td>6.05</td>
<td>1.45</td>
<td>8.23</td>
<td>4.38</td>
<td>4.59</td>
<td>2.03</td>
<td>1.47</td>
<td>3.31</td>
</tr>
</tbody>
</table>

proved cross section measurement with LUNA [7] and improved modeling of solar atmosphere elements (less volatile elements such as C, N, O) provided a big change in the prediction of neutrino fluxes [8]. Less C, N, O abundances correspond to smaller opacity, smaller temperature gradient, lower core temperature, and consequently result in smaller fluxes of $^7\text{Be}$, $^8\text{B}$ and CNO cycle neutrinos. Estimation of CNO cycle neutrino flux became smaller also by the new $S_{1,14}$ measurement and directly by the smaller abundances. During the last a few years, the estimated fluxes became lower by a factor of 3. See Table 1. The problem is that the new model with lower metal abundance predicts shallower convection region and the compatibility with helioseismology becomes much worse [9]. Thus, better determination of heavy element abundances in the solar atmosphere has produced a new solar model puzzle [8]. Importance of improving the accuracy of solar flux measurement is still unchanged.

Subdominant effects on solar neutrino deficit other than the LMA is still an open question. Various possibilities of time variation in the solar neutrino data were speculated again in these days. An example is a 2.4 $\sigma$ discrepancy of the Ga event rate before and after 1998 [10]. It can be explained by the existence of a sizable neutrino magnetic moment without causing any inconsistency on the other solar and reactor data. Examination of this kind of subdominant effects can be on a task list of future low energy solar neutrino experiments and a precision reactor experiment.

2. Reactor neutrinos

KamLAND experiment has contributed to solve the solar neutrino problem [11] and it is the only experiment which provided the evidence for spectral distortion due to the solar $\Delta m^2$ oscillation [12]. The evidence was the prerequisite for the accurate determination of the solar squared-mass-difference that followed. Its precision is however still limited by the statistics. On the other hand, main limitation to the accuracy of the mixing angle determination is coming from the systematic errors of fiducial volume and background estimation. A large fiducial volume error of 4.7% has been assigned [12] because a whole-volume calibration with radioactive sources was missing. KamLAND developed a new positioning device called “$4\pi$” which suspends a long pole with two wires. By controlling the length of the wires and tilting the pole, radioactive sources attached at a point of the pole can be located at all positions in the detector. Furthermore, the new purification system constructed for the KamLAND solar phase will eliminate the dominant background, $^{13}\text{C}$(α, n). Also a sophisticated analysis using larger (may be entire) fiducial volume is developed. All these efforts will contribute to improve the precision of oscillation parameter determination with reactor anti-neutrinos and will provide a sensitive test of CPT invariance in com-
parison with global fit of solar neutrino data.

The remaining unique unmeasured mixing angle $\theta_{13}$ is the target of very active investigations. Various experiments and observations are in fact have sensitivities to this parameter. Examples include long baseline accelerator experiments, reactor $\theta_{13}$ experiments, matter effect of neutrino oscillation in supernovae, supernova nucleosynthesis and so on. Many reactor $\theta_{13}$ experiments have been proposed because it is competitive, relatively cheap, and also is complementary with accelerator experiments [13]. In consideration of the balance of quickness and sensitivity, some projects were terminated and some are suspended. Now, apparently they are converged into 3 projects, the quickest Double CHOOZ [14] in France, the best sensitivity Daya Bay in China, and RENO in Korea [15]. They are planned to start gradually from 2008 (CHOOZ far) and reach the best sensitivity of $\sin^2 2\theta_{13} \simeq 0.01$ around 2013 (Daya Bay).

3. Geo-neutrinos

The earth is emitting anti-neutrinos that come from radioactive decays of uranium-, thorium-series and potassium. End point energies of the geo-neutrino are 3.27 MeV, 2.25 MeV and 1.31 MeV for $^{238}$U-series, $^{232}$Th-series and $^{40}$K, respectively, while reactor neutrinos extends up to $\sim$10 MeV. If one employs the well-established method with reactor neutrinos, the inverse beta decay $(\bar{\nu}_e + p \rightarrow e^+ + n)$, its reaction threshold is 1.8 MeV and neutrinos from $^{40}$K is unobservable, leaving it to future experiments with new detection methods. These radioactive decays are believed to be the major heat source of the earth and the bulk silicate earth model predicts about 20 TW heat production from them. Uncovering the nature of the heat source is very important to understand various aspects of earth formation and terrestrial dynamics; mantle convection relevant for earthquake and eruption, outer core convection driving terrestrial magnetism, etc. It will eventually lead to the construction of an observation-based robust earth model of formation and evolution.

Despite geo-neutrino observation is very useful to study the heat production in the earth, its detection hasn’t been achieved for a long time due to the very low interaction rate. The size of KamLAND is two orders of magnitude larger than the detectors used in the previous reactor experiments and it finally made experimental investigation of geo-neutrinos possible. KamLAND used anti-neutrino events with neutrino energy of above 3.4 MeV to estimate reactor neutrino contamination in the geo-neutrino region below 3.4 MeV. Using a tighter selection criteria, KamLAND observed 152 events in 750 days of live-time, where estimated number of background is $127 \pm 13$ (dominated by low energy component of reactor neutrinos and $^{13}$C($\alpha$, n) from radioactive impurities) [16]. The number of excess events, $25^{+19}_{-18}$, is consistent with bulk silicate earth model.
prediction, 19 events. It is not very significant yet, but KamLAND established the method to observe geo-neutrinos and it certainly opened the door to a new branch of science, the “neutrino geophysics”.

However, it is also clear that future geo-neutrino detectors are better to be located far away from nuclear reactors and, if possible, to have much larger size. It should also be noticed that translation of geo-neutrino event rate to the amount of radioactive heat production in the earth requires a model of radioactive source distribution. Therefore, it is highly desirable to have directional information of geo-neutrinos. A method for directional measurement of anti-neutrinos is under study to statistically distinguish between reactor neutrinos and geo-neutrinos from the crust and the mantle \[17\]. It will merit to improve the sensitivities on solar/geo-reactor anti-neutrinos, and may also be useful for advanced warning of supernova direction for optical observations, the SNEWS project \[18\].

There are many ways to proceed; A possibility is to use geo-neutrino data to verify or reject various models. Very sophisticated models have been created based on Preliminary Reference Earth Model and a crustal characterization with 2 x 2 degree unit for structural details and elemental abundances globally constrained with the BSE model for geochemical details, which lead to site specific predictions for geo-neutrinos \[19\]. The best thinkable possibilities include, for example, global observatory network, movable detector and the directional measurement. Hanohano project is a proposed deep ocean anti-neutrino observatory and the detector is designed to be movable \[20\]. If it is placed at around Hawaii, it should be able to probe geo-neutrinos from the mantle region in the earth. Its contribution is estimated to be as high as \(\approx 75\%\) because the oceanic crust is much thinner and less condensed with uranium and thorium than the continental one. It is also suggested \[20\] that, because it is movable, it may have other physics capabilities such as precise solar parameter (\(\Delta m^2_{21}\) and \(\theta_{12}\)) determination, \(\theta_{13}\) measurement, and even the mass hierarchy determination by moving to a preferred site.

4. Supernova neutrinos

The dynamics of supernova (SN) explosion is still a far-from-understood problem which is under active investigation. For its most recent status, see \[21\]. Though a great amount of efforts have been devoted to do realistic simulations of explosion by including various effects like multidimensional hydrodynamics, an improved neutrino transport, magnetic field, and rotation of star etc., the model simulations do not show explosion in a robust way. Therefore, we definitely need high-statistics data of neutrinos from future galactic SN to understand the mechanism of SN explosion.

Are we well prepared for the next supernova? The answer is, we think, yes and no. The answer is yes because SK is now fully reconstructed and KamLAND is continuously taking data. But, the question is; Do they alive 30—50 years from now, and even so are they enough to acquire necessary informations?

4.1. Supernova core diagnostics by neutrino observation

In the context of flavor-dependent reconstruction of supernova neutrino fluxes the answer to the above question is clearly \(\text{no}\). A SN at 10 kpc is believed to produce events in SK and KamLAND as tabulated in Table 2. The numbers are given only for the normal hierarchy, but it is very much dependent of the hierarchy \[25,26\]. Even if we assume that the mass hierarchy is determined by other means, reconstruction of luminosity and spectra of three effective species of SN neutrinos, \(\nu_e, \bar{\nu}_e, \text{ and } \nu_\mu = \nu_\tau\), does not appear to be possible with the observation by SK and KamLAND only. The most difficult part is to obtain spectral information of \(\nu_\mu\) because NC measurement is essentially “counting the number” experiment. An organized efforts are called for to define a well-thought strategy for future SN neutrino observation with practical set up of experimental arrays.

4.2. Relic supernova neutrinos

The relic SN neutrinos, the ones integrated over the past history of universe, will give us a mean for direct probe of the type II supernova rate. Then, it can be translated into the constraint on
Table 2
Calculated numbers of events expected without and with (in parenthesis, assuming the normal hierarchy) neutrino oscillation in SK with a 5 MeV threshold with a supernova at 10 kpc, which are taken from [22] and [23], respectively. The numbers in KamLAND [24] are given only for an alternative channel. $\nu_\mu$ and $\nu_e$ are assumed to be identical.

<table>
<thead>
<tr>
<th>reaction in SK</th>
<th>event No. in SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow e^+ + n$</td>
<td>8300 (6500)</td>
</tr>
<tr>
<td>$\nu_\mu + ^{16}O \rightarrow \nu_\mu + \gamma + X$</td>
<td>355</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu + ^{16}O \rightarrow \bar{\nu}</em>\mu + \gamma + X$</td>
<td></td>
</tr>
<tr>
<td>$\nu_e + e^- \rightarrow \nu_e + e^-$</td>
<td>200 (250)</td>
</tr>
<tr>
<td>$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$</td>
<td>60 (57)</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu + e^- \rightarrow \bar{\nu}</em>\mu + e^-$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>reaction in KL (not in SK)</th>
<th>No. in KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + ^{12}C \rightarrow ^{12}N^* + e^-$</td>
<td>2 (27)</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{12}C \rightarrow ^{12}B^* + e^+$</td>
<td>7 (7)</td>
</tr>
<tr>
<td>$\nu_\mu + ^{12}C \rightarrow ^{12}C^* + \nu_\mu$</td>
<td>50 (60)</td>
</tr>
</tbody>
</table>

the star formation rate in the universe which has a large uncertainty at the moment. For recent discussion, see e.g., [27,28,29,30] and an extensive references in [30]. Figure 2 summarizes the situation. Since the prediction by various models is either above or close to the limit placed by SK [31], there is an exciting possibility that it will be detected soon. Otherwise, we would need either Gd loading of SK III which is the subject of the next subsection, or a megaton class detector. See [32] for these points.

4.3. Gd-loaded Super-Kamiokande
A proposal of Gd-loaded SK (“GADZOOKS”) that has been put forward by Beacom and Vagins [33] is an extremely interesting option. If realized it will allow us to tag neutrons at $\sim$90% efficiency which tremendously enhances detectability of SN relic neutrinos as well as adding new power to flavor dependent reconstruction of $\nu$ fluxes. The real problem for this proposal is the experimental issues, such as whether one can guarantee that water transparency and radio purity can be maintained, and no damage is given to the water tank etc., as addressed in the talk in this workshop [34].

As it stands, neutrino physics around MeV energies is a very exciting active field. We must mention that while we tried to cover all the topics covered in the session but failed to discuss them in sufficient depth. Nonetheless, we hope that this manuscript succeeds to convey the exciting atmosphere felt by people in the community.

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