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NEUTRINO MASS AND OSCILLATIONS[1]

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Important recent discoveries in neutrino physics launched a new era in the search for 'physics beyond the Standard Model'. In particular, observation of the zenith angle dependence of the atmospheric neutrino flux, of the difference in the deduced flux of solar neutrinos based on their charged and neutral current interactions, and of the reduction in the flux of reactor antineutrinos at large distances convincingly show that neutrinos are massive and mixed. I briefly review the formalism and physics of the neutrino mass and mixing, and then concentrate on discussion of the KamLAND reactor neutrino experiment. That experiment, a continuation of a long tradition of studies involving neutrinos produced in nuclear reactors, is the first one to observe neutrino oscillations with a man-made and well understood source. I describe the detector, physics of the detection reaction, the determination of the reactor antineutrino flux and, naturally, the results and their implications.

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1 Oscillation formalism

The Standard Electroweak Model *postulates* that all neutrinos are massless, and consequently have conserved helicity (which is the same as chirality in this case) and that the separate lepton numbers for electron, muon, and tau flavors are conserved. This is a consequence of the assumed particle content of the model; left handed quarks and leptons form weak isospin doublets, while the righthanded quarks and *charged* leptons form weak singlets. The righthanded neutrinos are absent and without them neutrinos of all flavors are massless. Challenging this postulate of the vanishing neutrino mass has recently become a central issue in many disciplines of fundamental science, including particle and nuclear physics, cosmology, and astrophysics. The present talk is devoted to one particular aspect of this broad effort.

The main problem in neutrino physics today is the question whether neutrinos, like all charged fermions, have a mass. Since direct kinematic tests of neutrino mass lack at present the required sensitivity, the recent evidence for neutrino mass is based on the phenomenon of neutrino oscillations. If neutrinos are massive particles, the states with a definite mass (i.e., the "mass eigenstates" which propagate as plane waves in vacuum) are not necessarily the partners

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of the charged leptons that couple to the vector bosons $W^{\pm}$ in doublets (i.e., the weak or flavor eigenstates). The flavor eigenstates $|\nu_l\rangle$ will be in such a case linear superpositions of the mass eigenstates $|\nu_i\rangle$, which, in turn propagate according to

$$|\nu_l\rangle = \sum_i U_{l,i}|\nu_i\rangle \ , \ |\nu_i(t)\rangle = e^{-i(E_i t - p_i L)}|\nu_i(0)\rangle \simeq e^{-i(m_i^2/2E)L}|\nu_i(0)\rangle \ , \tag{1}$$

where the coefficients $U_{l,i}$ form the leptonic mixing matrix [3] and L is the flight path and in the last expression we assumed that the laboratory momenta and energies are much larger than the neutrino rest masses m_i, and skipped the common phase.

A neutrino which was created at $L = 0$ as a flavor eigenstate $|\nu_l\rangle$ is described at a distance L by

$$|\nu_l(L)\rangle \simeq \sum_{l'}\sum_i U_{l,i} e^{-i(m_i^2/2E)L} U^*_{l',i}|\nu_{l'}\rangle \ . \tag{2}$$

Thus, the neutrino of flavor l acquired components corresponding to other flavors l'. This is a purely quantum mechanical effect, a consequence of the coherence in the superposition of states in Eq.(1). The probability that the "transition" $l \rightarrow l'$ happens at L is obviously

$$P(\nu_l \rightarrow \nu_{l'}) = \left| \sum_i U_{l,i} U^*_{l',i} e^{-i(m_i^2/2E)L} \right|^2 \ . \tag{3}$$

In the two-flavor neutrino scenario, the oscillation probability is characterized by a single mixing angle θ, the amplitude $\sin^2 2\theta$ and by the mass-squared difference Δm^2, with the oscillation length

$$P(\nu_e \rightarrow \nu_x, L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \ ; \ L_{osc} = \frac{2.48 E_\nu(\mathrm{MeV})}{\Delta m^2(\mathrm{eV}^2)} \ \mathrm{meters} \ . \tag{4}$$

It turns out that the current experiments can be characterized by this simplified scenario. The applicability of the two-flavor analysis is a consequence of the large difference between the oscillation length associated with the mass difference Δm^2_{12} (explored by the study of solar neutrinos and by the KamLAND experiment described below) and the mass difference $\Delta m^2_{31} \sim \Delta m^2_{32}$ (explored by the study of atmospheric neutrinos). Empirically, $\Delta m^2_{31}/\Delta m^2_{21} \sim 30$. Observing the phenomenon of neutrino oscillation constitutes a proof that at least some neutrinos are massive particles. It also allows one to determine the mass squared differences Δm^2 and the mixing angles that characterize the matrix elements of the matrix U.

2 Existing evidence

The first hints that neutrino oscillations actually occur were serendipitously obtained through early studies of solar neutrinos and neutrinos produced in the atmosphere by cosmic rays ("atmospheric neutrinos"). In fact, the atmospheric neutrino measurements were a byproduct of the

[3] That matrix is often called Pontecorvo, Maki, Nakagawa, Sakata (PMNS) matrix to honor the early work on neutrino oscillations.

search for proton decay using large water Čerenkov detectors. So it is somewhat ironic that although there was substantial interest in searching for neutrino oscillations, the first evidence for this phenomena came from experiments designed for very different purposes. Recent studies definitively establish that the solar neutrino flux is reduced due to flavor oscillations, and so it is now clear that the first real signal of neutrino oscillations was the long-standing deficit of solar neutrinos observed by Ray Davis and collaborators using the Chlorine radiochemical experiment in the Homestake mine. While it took almost three decades to demonstrate the real origin of this deficit, the persistent observations by Davis *et al.* and many other subsequent solar-ν experiments were actually indications of neutrino oscillations.

The decay chain of $\pi^{\pm}$ produced in the upper atmosphere produce (through the subsequent μ-decay) a ν_μ, $\bar{\nu}_\mu$, and a ν_e (or $\bar{\nu}_e$). Thus, based on rather simple basic arguments one expects the ratio of ν_μ/ν_e events to be about ~ 2. However, the observed values were closer to ~ 1, the first hint of oscillations. The definitive proof came when the Super-Kamiokande experiment reported a clearly anomalous zenith angle dependence of the ν_μ events. The deduced values of $\sin^2 2\theta_{23} > 0.90$ (90% CL) indicate a surprisingly strong mixing scenario, completely contrary to the quark sector, where the mixing between generations is generally small. The failure to observe $\bar{\nu}_e$ disappearance at CHOOZ and Palo Verde in the region near $|\Delta m^2_{31}| \simeq 0.0025$ eV^2 implies that the ν_μ disappearance observed by Super-Kamiokande does *not* involve substantial ν_e appearance. Thus, it would seem that the ν_μ's must be oscillating into ν_τ.

The solar neutrino measurements included radiochemical experiments sensitive to integrated ν_e flux such as the Chlorine and Gallium experiments. Live counting was developed by the Kamiokande and then the SuperKamiokande experiments, based on neutrino-electron scattering, enabling measurements of both the flux and energy spectrum. All these experiments reported a substantial deficit in neutrino flux relative to the "Standard Solar Model" (SSM). Finally, the convincing proof of neutrino flavor change became reality when the SNO experiment was able to determine both the ν_e flux through the charged current (CC) deuterium disintegration, and the total neutrino flux through the neutral current (NC) deuterium disintegration. The results demonstrate very clearly that the total neutrino flux ($\nu_e + \nu_\mu + \nu_\tau$ as determined from NC) is in good agreement with the SSM, but that the ν_e flux is suppressed (as determined from CC). Furthermore, the observed value of ν_e flux and the observed energy spectrum, when combined with the other solar-ν measurements strongly favor another large mixing angle scenario at a lower value of $\Delta m^2_{21} \sim 10^{-5}$ eV^2.

This brief review contains no references to the original papers. An interested reader can find more details either in the review [1] or in the Review of Particle Physics [2].

3 Reactors as $\bar{\nu}_e$ sources

Nuclear reactors produce $\bar{\nu}_e$ isotropically in the β decay of the neutron-rich fission fragments. All reactor $\bar{\nu}_e$ detectors take advantage of the relatively large cross-section and specific signature (positron events correlated in space and time with the neutron capture event) of the inverse-β-decay reaction $p + \bar{\nu}_e \rightarrow n + e^+$. This cross-section is shown in Figure 1 as function of the neutrino energy along with the neutrino flux at the reactor and the resulting interaction rate.

Reactor-based oscillation searches can only be of $\bar{\nu}_e$ -disappearance type since the neutrino "beam" does not have sufficient energy to produce muons (or taus). At the same time, the low

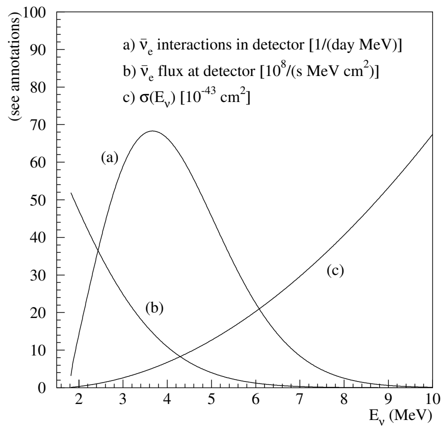

Fig. 1. Reactor $\bar{\nu}_e$ flux, inverse beta decay cross section, and $\bar{\nu}_e$ interaction spectrum. Keys a) and b) refer to 12 tons fiducial mass detector located 0.8 km from 12 GW$_{th}$ power reactor.

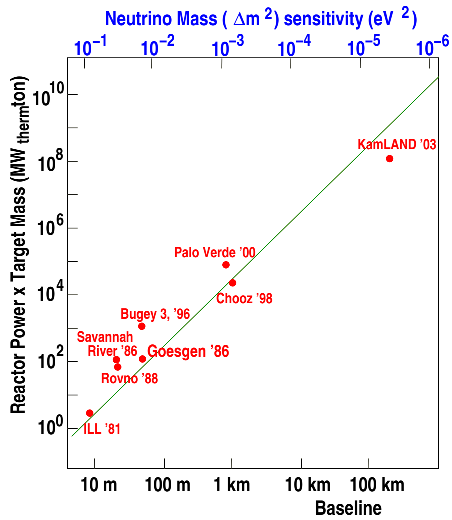

Fig. 2. Neutrino Δm^2 sensitivity as a function of total reactor power and detector fiducial mass. The fiducial-mass×power necessary for the experiment grows with the square of the baseline. The past experiments are labeled by the name of the reactor complex used and the year.

energy neutrinos provide us with a unique opportunity to probe the lowest regions of Δm^2, even comparable to the Δm^2 explored in the solar neutrino experiments.

For the reactor-based experiments the accurate determination of the $\bar{\nu}_e$ spectrum and its absolute normalization are essential ingredients. The determination of the $\bar{\nu}_e$ yield proceeds, schematically, in three steps. First, the thermal power of each reactor core is measured. Based on such measurements, and starting from the initial fuel composition, the burn-up state can be computed as function of time. In the second step the neutrino spectrum is derived from the fission rate. Finally, as the last step, the neutrino spectrum emitted by the reactors must be converted into an estimate of the experimental observable, the positron spectrum in the detector.

Since in all reactor experiments one measures the positron spectra, and not directly the $\bar{\nu}_e$ spectra, one has to understand quantitatively how these are related. In other words, one has to know the cross section of the 'detector' reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The cross section can be expressed, to the lowest order, in terms of the neutron lifetime and the phase space factor $f^R_{p.s.} = 1.7152$ as

$$\sigma^{(0)}_{tot} = \frac{2\pi^2/m_e^5}{f^R_{p.s.}\tau_n} E_e^{(0)} p_e^{(0)} , \tag{5}$$

where $E_e^{(0)} = E_\nu - (M_n - M_p)$. In this way, the cross section is tied directly to the neutron lifetime, τ_n, known to 0.2%. The relatively small energy dependent corrections, including the

QED effects of order α, are well known.

Altogether, the expected signal with no oscillations is known to about 2%. And the early reactor experiments, shown in Fig. 2 observed, within errors, just the signal one expects for $\bar{\nu}_e$ that do not oscillate. Detailed description of them, and the whole set of issues related to reactors as $\bar{\nu}_e$ sources, could be found in Ref. [3].

4 KamLAND experiment

The exploration "in a laboratory setting" of the parameters relevant to the solar neutrino oscillations is particularly challenging by the huge L/E_ν required. However, the very low energy of reactor neutrinos make such oscillation experiment possible. In order to explore it one needs a Δm^2 sensitivity of at least 10^{-5} eV^2 at a large mixing angle. We refer to Figure 2 to see that a $\approx$ 100 km baseline is needed and this drives the power$\times$fiducial-mass product in the 10^8 MW$_{th}\times$tons range. Clearly a large detector has to be used in conjunction with very many nuclear reactors. The Kamioka site in Japan has the required properties; there is an anti-neutrino flux of $\simeq 4 \times 10^6$cm^{-2}s^{-1} (or $\simeq 1.3 \times 10^6$cm^{-2}s^{-1} for $E_{\bar{\nu}} > 1.8$ MeV, the detection reaction threshold) from nuclear reactors. 80% of this flux derives from reactors at a distance between 140 km and 210 km.

The KAMLAND detector is housed in the cavity built for the Kamiokande detector under the summit of Mt. Ikenoyama in the Japanese Alps, about 50 km south of the town of Toyama. The rock overburden is more than 1,000 m in any direction. A cutout view of the KAMLAND detector is shown in Fig.3. The fiducial volume consists of a sphere containing 1000 tons of liquid scintillator. The scintillator container is a thin plastic-walled balloon of 6.5 m radius. The buffer acts as a shield against external background, and muon veto is based on the water Čerenkov detector external to the steel sphere carrying the PMT.

The inner detector is calibrated with γ-ray sources deployed at various positions along the vertical axis. The observed energy resolution is $\sim$7.5%/$\sqrt{E(\mathrm{MeV})}$. The event positions are reconstructed from the relative times of PMT hits. Vertex reconstruction performance throughout the detector volume is verified by reproducing the uniform distribution of 2.2 MeV capture γ's from spallation neutrons.

Great effort was devoted to minimize the internal background caused by the radioactivity in the liquid scintillator. That effort was a success as the *in situ* measurements show that the ^{238}U and ^{232}Th content is an unprecedented $(3.5 \pm 0.5) \times 10^{-18}$ g/g and $(5.2 \pm 0.8) \times 10^{-17}$ g/g, respectively. The accidental background, obtained from the observed flat distribution in the delayed time window, is comfortably low.

The data taking began in January 2002, and the first data set, containing 145 livetime days was analyzed and published in early 2003 [4]. The expected number of reactor neutrino events (in the absence of neutrino oscillations) for this data set is 86.8 ± 5.6, while only 54 events were observed. The ratio of the number of observed reactor $\bar{\nu}_e$ events to that expected in the absence of neutrino oscillations is $\frac{N_{obs}-N_{BG}}{N_{expected}} = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$. The probability that this first KamLAND result is consistent with the no disappearance hypothesis is less than 0.05%. Fig. 4 shows the ratio of measured to expected flux for KamLAND as well as previous reactor experiments. Clearly, the KamLAND result is fully consistent with expectations based on the analysis of the solar neutrino data and on the assumption of neutrino oscillations. This represents

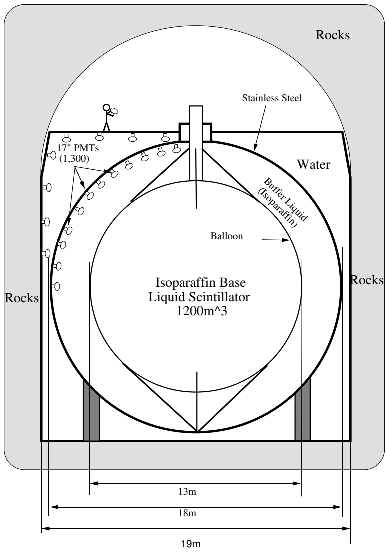

Fig. 3. Schematic cross-section of the KamLAND detector.

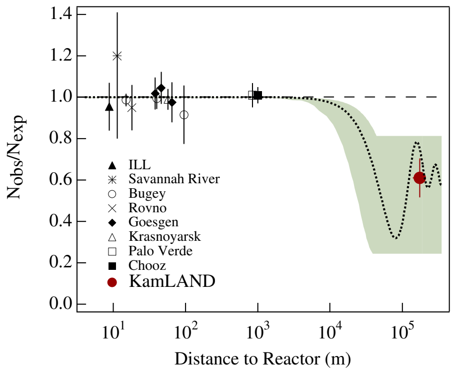

Fig. 4. The ratio of measured to expected $\bar{\nu}_e$ flux from reactor experiments. The shaded region indicates the range of flux predictions corresponding to the solar neutrino data, and the dotted curve is a best-fit of solar neutrino data.

a first observation of oscillations employing a man-made and well understood neutrino source.

A second and most recent data set [5] is based on 515 livetime days and offers even better evidence for oscillations since the $\bar{\nu}_e$ spectrum distortion is observed as well. That data set contains 258 observed events, with 365 ± 24 expected if there were no oscillations. That result is inconsistent with the simple $1/r^2$ propagation at the 99.995% CL.

To better visualize the spectrum distortion in Fig. 5 the ratio of the observed $\bar{\nu}_e$ flux to the no-oscillation expectation is plotted against L_0/E, with L_0 = 180 km. Even though the events come from reactors distributed over different distances, L_0 approximates the distance where most of the reactors are located. The figure shows that the oscillation hypothesis is clearly preferred when compared to the alternatives.

5 Conclusions

Once we are satisfied that oscillations involving electron neutrinos have been observed, we can analyze the data to determine the mass square difference Δm^2_{21} and the mixing angle θ_{12}. Moreover, one can combine the reactor data from KamLAND and the solar neutrino data under the assumption of CPT invariance. The results of the corresponding fit are shown in Fig. 6. The best fit parameters are $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.40^{+0.10}_{-0.07}$ including the allowed one sigma parameter range. Hence, KamLAND experiment not only strengthened the conviction

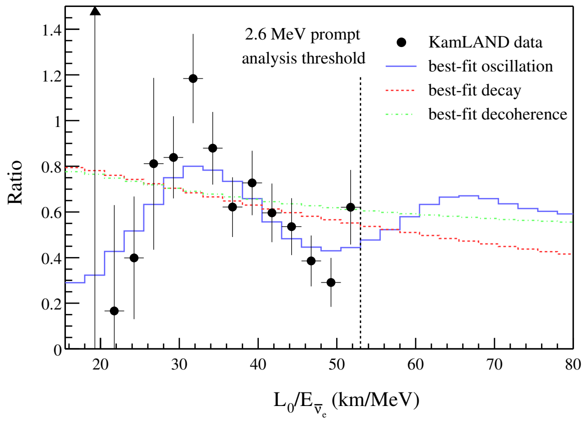

Fig. 5. Ratio of the observed $\bar{\nu}_e$ flux to the no-oscillation expectation versus the distance over energy L_0/E. The KamLAND data points are plotted with L_0 = 180 km, as if all detected $\bar{\nu}_e$ were due to a single reactor at that distance. The curves show the expectations for the best-fit scenarios with oscillations, and with alternatives of neutrino decay and decoherence model. Adopted from [5].

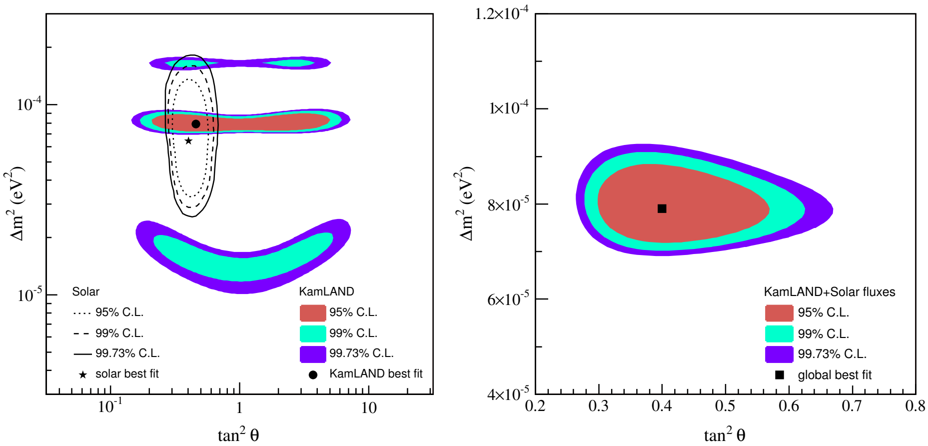

Fig. 6. (a) Neutrino oscillation parameter allowed region from KamLAND data (shaded) and from solar neutrino experiments (lines). (b) Results of a combined analysis in the two-neutrino scenario. Adopted from [5].

that neutrino oscillations are real, and hence neutrinos are massive, but opened the era of the precision neutrino physics.

Naturally, despite the triumphs described above, significant challenges remain. We do not understand why neutrinos are so much lighter (by a factor of $\sim 10^6$) than the other (charged) fermions. One possibility, preferred by many theorists, is that neutrinos are Majorana particles, identical to their antiparticles. A proof of Majorana nature would be an observation of the total lepton number violation. The most likely process where that might happen is the neutrinoless double beta decay. Large experimental effort is devoted to attempts to observe this rare nuclear process.

Further exploration of the mixing matrix is another challenge. Of particular interest is the determination of the so far unknown mixing angle θ_{13} that characterizes the coupling of electron neutrinos to the third, isolated, mass eigenstate. We know that this mixing angle, unlike the other two, is small, but it is unknown how small it really is. A slew of new precision reactor experiments is proposed to determine, and severely constrain, that angle.

Provided that θ_{13} is nonvanishing, it might be possible to observe the CP violation in the lepton sector. The right tool for that would be a long baseline accelerator experiment. Several such experiments are planned. Altogether, next decade promises to add new discoveries to those we witnessed recently.

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