The CHOOZ and KamLAND Reactor Neutrino Experiments

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Neutrinos were discovered at reactors forty years ago, and reactors remain an important tool for the investigation of neutrinos. This is primarily due to the intense flux which is known to better than 2%, and has pure electron flavor. Distant detectors can have sufficient count rates to test the hypotheses that the cosmic ray anomaly (CRA–too few muon flavored neutrinos from the atmosphere) and the solar neutrino anomaly (SNA–too few electron flavored solar neutrinos) are due to the oscillations of neutrinos with mass. The CHOOZ experiment tests in the region of the CRA with a detector one kilometer from reactors. It is sensitive to oscillations resulting from squared neutrino masses of $10^{-3}\mathrm{eV}^2$, and has seen no electron flavor oscillations. KamLAND is 160 Km from reactors and tests down to $10^{-5}\mathrm{eV}^2$–the region of the SNA. It is also sensitive to neutrinos from the sun, and high purity scintillator will allow detection of solar neutrinos down to lower energies than is possible in water cherenkov detectors. Construction of the apparatus has begun and the experiment with be started in the year 2001.

I. INTRODUCTION

A. Reactor Neutrinos

Beta decay in reactor fuel elements creates an isotropic flux of pure electron flavored antineutrinos with a well defined energy spectrum. The absolute flux has been calculated [1] and experimentally shown to be in agreement [2] to better than 2%. The total flux is about 2x10^{20} $\bar{\nu}_e/sec/GW$ in the range 1.8–7.8 MeV. Thus, reactors produce an intense beam of antineutrinos having well known characteristics. By contrast, atmospheric neutrinos have flux, spectral and flavor uncertainties which are an order of magnitude less well known. Solar neutrinos also bear flux uncertainties due to imperfect solar models and the MSW effect. Because reactors provide a well controlled 'beam' of neutrinos, they provide a means to test the findings of atmospheric and solar neutrino experiments, independently of their respective neutrino sources.

The reactor experiments described here detect antineutrinos using the inverse beta decay reaction,

$$\begin{array}{rcl} \bar{\nu}_{\mathrm{e}} + \mathrm{p} & \longrightarrow & \mathrm{e}^+ + \mathrm{n} \\ & & \mathrm{e}^+ + \mathrm{e}^- \quad\;\; \longrightarrow \;\gamma\,\gamma \\ & & \mathrm{n} + \mathrm{nucleus} \;\longrightarrow\; \mathrm{capture}\,\gamma(\mathrm{s}) \end{array}$$

The threshold for the first reaction is 1.8 MeV, giving zero kinetic energy to the positron, which then decays into 2 γ, which deposit 1.02 MeV in the surrounding detector; the neutron has little kinetic energy and captures after thermalization. If the neutron captures on hydrogen the capture time constant is $190\mu s$ (KamLAND), but CHOOZ is doped with 0.1% gadolinium to reduce this to $30\mu s$, resulting in ~ 3 γ with total energy of 8 MeV. In both cases the distinct sequence of pulses creates a clean event signature–even at threshold, where the minimum observed energy deposit is 1.02 MeV . The cross-section for the inverse beta decay reaction is known to better than 2.5%.

B. Neutrino Oscillations

Evidence of neutrino oscillations comes from atmospheric neutrinos [3]. The atmospheric muon-flavored neutrino flux should be roughly twice the electron-flavored neutrino flux, but is found to be about the same. Two possible explanations are,

1. ν_μ disappearance, possibly to ν_τ.

2. $\nu_\mu \leftrightarrow \nu_e$ with muon–electron flavor mixing giving a relative depopulation of muon flavor.

CHOOZ has a value for L/E of about 300 meters/MeV, comparable to that for the atmospheric neutrinos. If scenario two is correct, there should be a reduction in the antineutrino flux observed by CHOOZ, as well as a distortion of the energy spectrum which depends on the distance from the reactor. Two component neutrino oscillations predict that the the factor is

$$P_{ee} = 1 - \sin^2 2\theta \sin^2(1.27\delta m^2 L/E)$$

where P_{ee} is the probablility that an antineutrino or energy E(MeV) will retain its flavor at a distance L(m) from the source. The mass parameter, δm^2, is the difference between the mass-squared of the two fundamental neutrinos. The magnitude of the flavor mixing is defined by $\sin^2(2\theta)$. $\delta m^2 \sim 0.001$–$0.01 eV^2$ and $\sin^2(2\theta) \sim 0.8$ are implied by the CRA and these values would cause significant flux and spectral changes at the CHOOZ detector, if the the second of the two explanations is true. The absence of oscillations at CHOOZ would imply (and does) [4] that the first explanation for the CRA is more likely.

The existence of neutrino oscillations also is implied by solar neutrino detection experiments [5], which detect only half, or less, than the expected number. Assuming that the models of neutrino production in the Sun are correct, there are various possible values [6] for the mass-mixing parameters of neutrino oscillations that are compatible with existing solar neutrino measurements:

1. LMA, the large mixing angle MSW solution –$\sin^2 2\theta \sim 1$, $\delta m^2 \sim 10^{-5} eV^2$.
2. SMA, the small mixing angle MSW solution–$\sin^2 2\theta \sim 10^{-3}$, $\delta m^2 \sim 10^{-5} eV^2$.
3. LOW, the low δm^2 solution–$\sin^2 2\theta \sim 1$, , $\delta m^2 \sim 10^{-7} eV^2$.
4. JS, the 'just so' solution–$\sin^2 2\theta \sim 1$, $\delta m^2 \sim 10^{-10} eV^2$.

KamLAND, by virtue of its 16O Km distance from reactors, is sensitive to a mass parameter about 100 times smaller than CHOOZ', or about $10^{-5}eV^2$. The LMA solution (from the above list) has mass and mixing parameters that would cause significant changes in the observed flux rate and spectrum of the reactor antineutrinos. Measuring these is the first objective of KamLAND. It requires that the scintillator impurity be less than 10^{-14} g/g of U^{238}, Th^{232}, and K^{40}. The reactor antineutrino oscillation experiment constitutes a test of the neutrino properties in the LMA solution which is completely independent of solar neutrino models and the MSW Effect.

The second objective is measuring Be^7 neutrinos from the Sun. Recoil electrons from elastic neutrino–electron scattering in KamLAND result in a continuous spectrum with an 'edge' at the maximum energy deposit of 0.66 MeV. Backgrounds are high at this low energy, demanding that scintillator impurity be better than 10^{-16} g/g for U and Th, and two orders better for K^{40} and C^{14}. Techniques for achieving this purity have been developed by Borexino [7] but only the full experiment can really tell if purification has been successful. If so, the Be^7 flux can distinguish the LMA and SMA solutions by rate differences, while the LOW solution should show day–night variations and the JS solution should show anomalous seasonal variations. If both objectives are achieved, KamLAND could make a statement about all of the mass-mixing combinations that satisfy existing experiments.

II. THE CHOOZ EXPERIMENT

The CHOOZ experiment was designed to search for neutrino flavor oscillations in the mass-mixing ranges of the CRA (Cosmic Ray Anomaly). A 50% reduction in antineutrinos would be expected if scenario 2 ($\nu_\mu \leftrightarrow \nu_e$) is true. The observation of no reduction of antineutrinos leaves scenario 1 as the best explanation of the CRA.

A. Description of CHOOZ detector

The CHOOZ detector (Figure 1) is 1 km from two reactors in Chooz, France, which have a maximum thermal power of 8.5 GW. The detector is 100 m below ground in a tunnel which was turned into a laboratory by France's electrical company, EdF. The detector consists of a steel cylinder recessed in the tunnel floor, containing 115 tons of scintillator, covered by 14 cm of iron and surrounded on bottom and sides by low activity sand. Five tons of gadolinium loaded scintillator in Region 1 is contained in a transparent acrylic vessel. This is surrounded by 20 tons of normal scintillator (Region 2) and viewed by 192 PMTs mounted on the 'geode', an optically closed structure. The remaining 90 tons of scintillator (Region 3) serves as an active veto and is viewed by 48 PMTs. Photomultiplier pulse heights and times are encoded in ADC and TDC units, and a history of detector activities is recorded in the fWFD and sWFD (fast and slow wave form digitizers), which also provide considerable hardware redundancy.

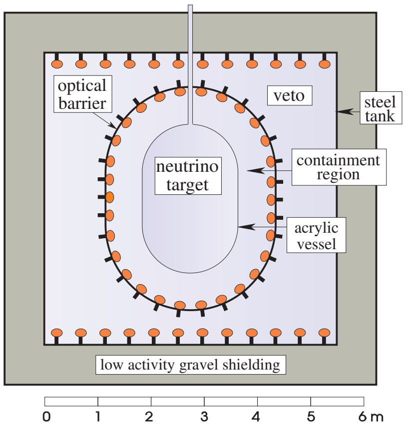

FIG. 1. The CHOOZ Detector.

The photomultipliers, EMI9351, have high gain first dynodes, allowing single photoelectrons to be resolved. Time jitter for single photoelectron pulses is about 3 ns which is somewhat better than the scintillator time constant in region 1, and useful for event reconstruction. In region 1 the scintillator contains about 0.1% of natural gadolinium by weight, reducing the neutron capture time to about 30 μs, and increasing the gamma energy release for capture to 8 MeV. The corresponding numbers for capture on hydrogen are 190 μs and 2.2 MeV; the addition of gadolinium raises the neutron pulse above normal natural background energies and shortens the delay for neutron capture after antineutrino capture events. Both effects reduce accidental background. Region 2 scintillator light output is well matched to Region 1. Gamma rays escaping from Region 1 interact in Region 2 and are seen by the photomultipliers, negating a possible loss of energy resolution. Region 3 scintillator is used to reject cosmic ray background and also serves as a passive shield, greatly reducing the singles rates of the 192 PMTs which view the internal regions.

Event triggers are generated in a nearby electonics hut, where the data are also collected and assembled for each event. An event trigger is defined off-line to be a 1.5-8 MeV pulse (level 1 coincidence) when all PMTs are summed, followed by a 6-12 MeV pulse (level 2 coincidence) within 100 μs. The first covers most of the positron energies produced by the reactor antineutrinos, while the second defines a delayed neutron capture on Gd. The on-line hardware relaxed these requirements so that both level 1 and level 2 coincidences had a summed energy threshold somewhat below 1.5 MeV, resulting in trigger rates that are about 0.5 /sec for this class of trigger.

Calibration was performed by inserting radioactive gamma and neutron sources into stainless steel tubes that entered Region 1 and 2, and were sealed at the end. Permanently installed internal 'flashers' were excited by light fed to them through UV optical fibers from a nitrogen laser for additional calibration tests. Calibrations and data runs enabled us to determine that the detector's energy resolution was better than 10% at 2 MeV and that the reconstruction accuracy was about 10 cm. This allowed clean cuts to be placed on energy (see above), event location wrt the PMT surface (> 30 cm), positron and neutron vertex distance (< 100 cm), and neutron delay time (> 2 and < 99 μs).

B. Old and New Results

Last year [4] we reported our first results from the running period 3/97—10/97. 1433 events were collected at power levels from 0–8 GW. A good linear fit gives 1.2 background and 25.5 signal events per day at full power (8.5 GW). This resulted in and oscillation probability of $0.98 \pm (\text{stat.})0.04 \pm 0.04(\text{sys.})$, consistent with no oscillations. The mass–mixing plot of Figure 2 shows our exclusion limits which enclose the composite region for which oscillations were observed by Kamiokande and SuperKamiokande. We concluded that these oscillations could not be explained by $\nu_\mu \leftrightarrow \nu_e$, and therefore were most likely due to $\nu_\mu \to \nu_X$, where 'X' stands for some non-electron flavor.

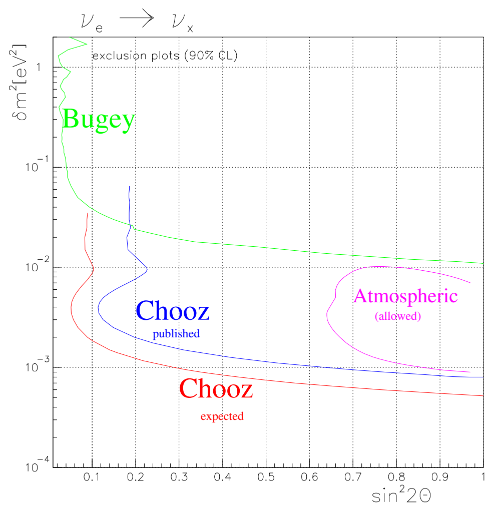

FIG. 2. Mass–mixing contour plot for CHOOZ

Recent results from SuperKamiokande [8] directly observe effects consistent with ν_μ disappearance oscillations in this channel. Preliminary results from the Palo Verde reactor experiment [9] are also in agreement with CHOOZ.

CHOOZ is now analyzing the final set of data, which is almost double the size of the published sample. Systematic and statistical errors will be reduced to about 2.5%, due to better understanding of our efficiency, detector composition, and numerous small improvements. In addition, several different analyses have been done at different institutions. One analysis uses only data from the fastbus TDC and ADC channels for the individual PMTs and a completely new reconstruction algorithm. Another uses only data from the fast wave–form digitizers (fWFD). Yet another utilizes fastbus TDC data and a different set of ADCs operating on patches of 24 PMTs. They are all in agreement on event rates, though the data sets are somewhat different, due to different down periods for the various hardware units. This indicates that have been no significant hardware or reconstruction inefficiencies in the main analysis.

A limit on oscillations can be gotten from a comparison of the antineutrino signal from the two different reactors at CHOOZ. This does not depend on the absolute reactor flux calculations and our detector efficiency; essentially it is almost free of systematic errors. The two reactors are at 990 and 1100 meters from the detector, and a large fraction of our data are taken with one reactor at high power and the other at low power. A difference in rates would indicate that neutrinos oscillate over a 110 m path length. Figure 3 shows the limit imposed by comparing these two sets of data. Though preliminary, it excludes the full region of oscillations originally suggested by Kamiokande, but not that of Superkamiokande.

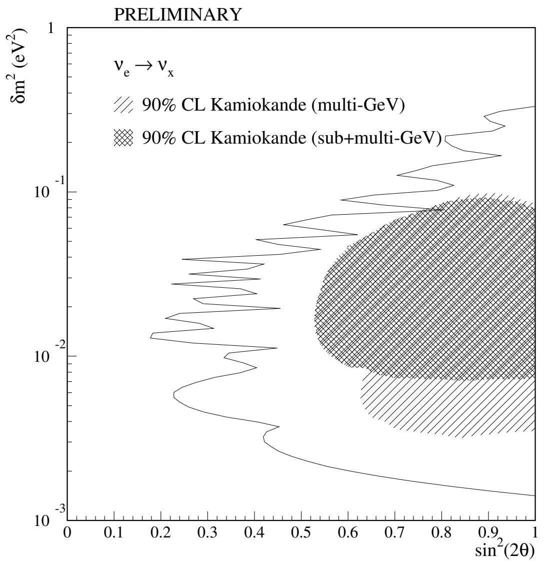

FIG. 3. Mass–mixing limits for two reactor comparison of rates.

It seems convincing that electron neutrinos oscillate weakly at best, leaving muon neutrino oscillation into tau or sterile neutrinos as the only simple solution(s) to the CRA.

III. THE KAMLAND EXPERIMENT

The KamLAND detector [10] is sensitive to antineutrino oscillations in the mass-mixing regions suggested by the Solar Neutrino Anomaly (SNA). Antineutrino events from reactors at 160 Km will allow the large mixing angle MSW solution to the SNA to be tested without the uncertainties of the solar model and MSW assumptions. Solar neutrinos can also be observed, and the observation of the ^{7}Be line would allow tests of the other solutions to the SNA.

A. The KamLAND Design

KamLAND is optimized for studying oscillations with reactor neutrinos. The detector , shown in Figure 4, is under construction at the former site of the Kamiokande detector in Japan. It is shielded from cosmic rays by 1000 meters of rock, and from radioactivity in the rock by $\sim$2 meters of water viewed by 200 PMTs acting as a veto. The detector is contained by a stainless steel vessel of radius 18 m. Inside there is a 2.5 m buffer of isoparaffin surrounding a 6.5 m radius transparent balloon filled with 1 kT of scintillator that forms the neutrino target. There are 1900–17 in. PMTs on the inner surface of the steel sphere viewing this inner region of scintillator and buffer. The scintillator most likely to be used is composed of PPO, a wave length shifter, dissolved in mineral oil and pseudocumene, which will give a detected light of at least 150 pe/MeV.

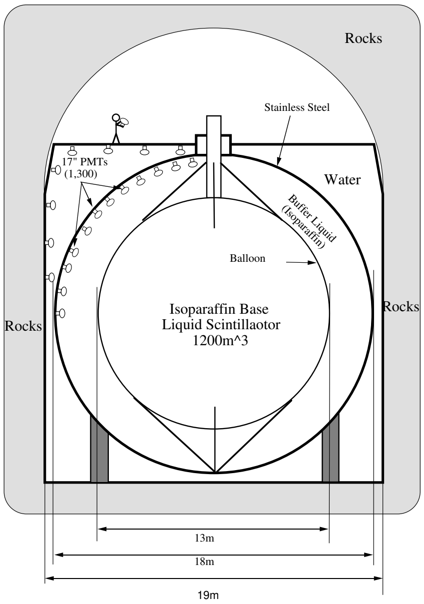

FIG. 4. The KamLAND detector. (There will be 1900 PMTs in the detector).

B. Reactor Signal and Background

Reactor antineutrino capture events on protons will be detected as in CHOOZ. The events give a clean signature which is a delayed coincidence between the positron and γ(2.2 MeV) from the neutron capture on hydrogen. time of 190 μs. Events in the buffer will give low light output and form no coincidence.

The reactors nearest to KamLAND that contribute significant antineutrino flux are all farther than 160 Km, and are equivalent to a reactor of 130 GW at 180 Km. The estimated number of observed events from reactor antineutrinos is about 774 events/year for no mixing. The expected positron energy spectrum for various values of the mass and mixing parameters is shown in Figure 5.

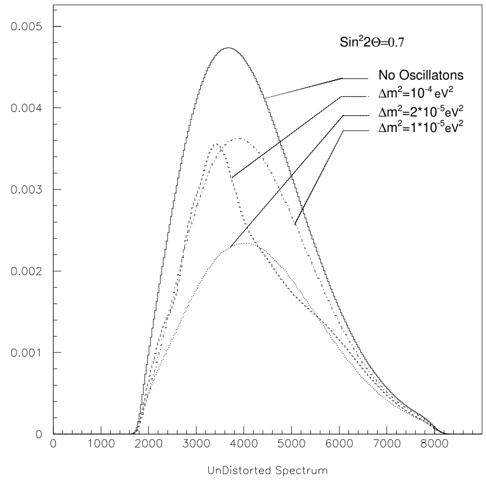

FIG. 5. The reactor neutrino spectrum as modified by neutrino oscillation parameters.

Background has been calculated independently by UNM/Stanford and Tohoku Univ and we have achieved rough agreement. A purity of 10^{-14} g/g of U, Th, ^{40}K results in background of 0.1/day compared to the reactor signal of 2/day. This purity level is 100 times worse than is required to do solar neutrino physics. Limits on the mass mixing parameters after 3 years of running are shown in Figure 6. Essentially they cover the large mixing MSW solar neutrino solution to the SNA.

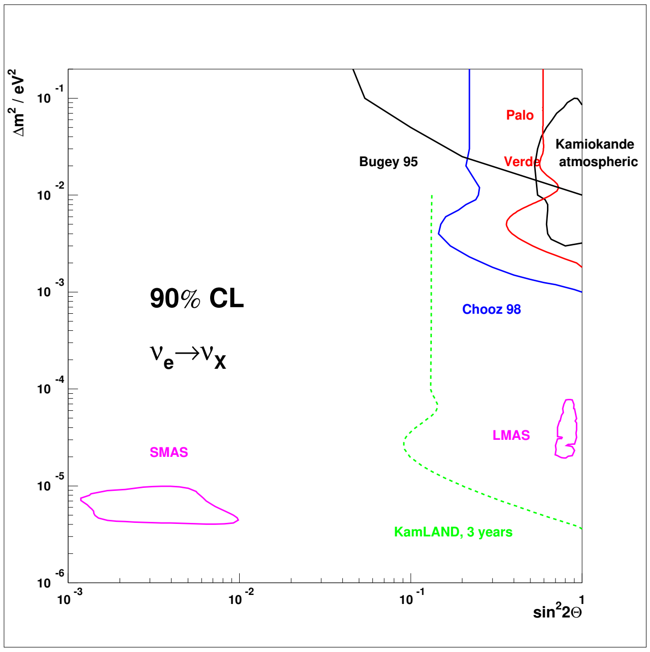

FIG. 6. The Mass–mixing sensitivity of KamLAND. Palo Verde is still running.

C. Solar Signal and Background

Solar neutrino events are detected by observing electron recoils from $\nu - e$ scattering. The signature for these events is a step in the collected energy spectrum of recoil electrons at about 600 KeV. on top of a smooth background. Extremely pure scintillator is required to reduce the background to a level that allows the step to be seen. Hundreds of events per day are expected from ^{7}Be in the sun–assuming no oscillation.

The major detector backgrounds are contained in the scintillator; external backgrounds from rock, photomultipliers and detector materials are smaller because of absorption of external radiation by the water and buffer oil regions. Radon is a special case because of its mobility, and special care must be taken to seal the detector, remove radon from the scintillator, and stop its migration through the balloon.

The solar signal and major detector backgrounds are shown in Figure 7. Typically, as the energy decreases both the signal and the background increase. Scintillator purity of 10^{-16} g/g is sufficient to lower the background so that it is similar in magnitude to the signal. At this purity level the ^{7}Be solar model predicts 466 events/day on top of a background of 438 counts from other sources. The LMA and SMA solution to the SNA predict the ^{7}Be contribution of 262 and 98 events, respectively–a significant difference. The LOW and JS solutions would have a distinctive day-night and seasonal variations as signatures of their dominance. Thus, the high purity allows very powerful tests of the 'solutions' to the SNA.

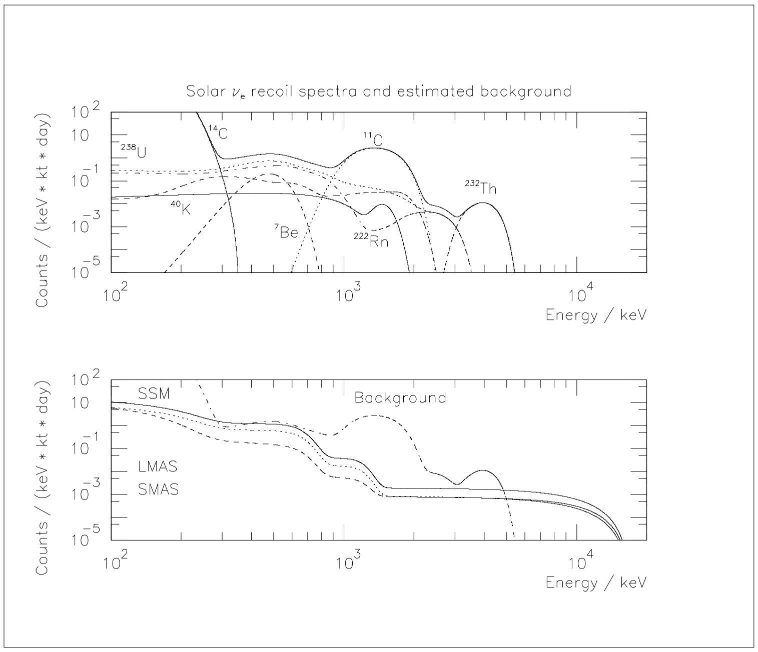

FIG. 7. Background spectra (top) and the spectra of solar neutrinos (bottom) with the sum of backgrounds overlaid.

IV. FUTURE

There are mysteries to solve in neutrino oscillations that should be solved in the next five years. SuperK is running, SNO will be running in the near future and both Borexino and KamLAND, with their unique abilities will be turned on in the year 2001. Within 3 years of this date a much clearer picture of neutrino mass will be available.

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[1] Schreckenbach *et al.*, Phys. Lett.**B160,** 325 (1985).
[2] Y. Declais *et al.*, Phys. Lett. **B338,** 383 (1998).
[3] R. Becker-Szendy *et al.*, Phys. Rev. **D46,** 3720. (1992); K. S. Hirata *et al.*, Phys. Lett. **B280,** 146(1992); Y. Fukuda *et al.*, Phys. Lett. **B433,** 9 (1998).
[4] M. Apollonio *et al.*, Phys. Lett. **B420,** 397 (1998).
[5] B. T. Cleveland, *et al.*, Astropys. J. **496,** 505 (1998); M. Cribier, Nucl. Phys. Proc. Suppl.**70,** 284 (1999); D. N. Abdurashitov *et al.*, Nucl. Phys. Proc. Suppl. **48,** 299 (1996); Y. Fukuda *et al.*, Phys. Rev. Lett. **77,** 1683 (1996); Y. Fukuda *et al.*, Phys. Rev. Lett. **81,** 1158 (1998).
[6] J. N. Bahcall and P. I. Krastev, Phys. Lett. **B436,** 243 (1998).
[7] J. B. Benziger *et al.*, "A Scintillator Purification System for a Large Scale Solar Neutrino Experiment", submitted to NIM.
[8] Y. Fukuda *et al.*, Phys. Rev. Lett. **81,** 1562 (1998).
[9] G. Gratta, to appear in the proceedings of Wein 99, Cape Town, South Africa, January 1999.
[10] KamLAND Proposal, A. Suzuki (Spokesman), Tohoku Univ., Japan.