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PRESENT AND FUTURE OSCILLATION EXPERIMENTS AT REACTORS

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A report is presented on recent progress and developments (since the NANP'99 Conference) in the current and future long baseline (~ 1 km) and very long baseline ($\sim 100-800$ km) oscillation experiments at reactors. These experiments, under certain assumptions, can fully reconstruct the internal mass structure of the electron neutrino and provide a laboratory test of solar and atmospheric neutrino problems.

Доклад посвящен прогрессу (после конференции NANP'99) в исследованиях по поиску осцилляций нейтрино на дальних (~ 1 км) и сверхдальних ($\sim 100-800$ км) расстояниях от реакторов. Эти исследования позволяют при некоторых допущениях полностью реконструировать массовую структуру электронного нейтрино и обеспечивают лабораторную проверку проблем, связанных с солнечными и атмосферными нейтрино.

INTRODUCTION

In this report we discuss the following experiments and projects:

- The first long baseline experiment at CHOOZ (France, Italy, Russia, the USA) [1] completed soon after NANP'99 (final results).
- The long baseline Palo Verde experiment in Arizona [2] (current results). The experiment was scheduled to be finished in 2000.
- The long baseline two detector project Kr2Det for the Krasnoyarsk underground (600 mwe) site aimed to search for very small mixing angles [3]. The project is in a R&D stage.
- The very long baseline experiment KamLAND at Kamioka (Japan, the USA) [4]. The data taking can start in 2001.

At this Conference the very long baseline experiment BOREXINO at Gran Sasso, has been reported in detail by T. Hagner, the possibilities of testing the LSND oscillations in a reactor experiment were considered by V. Sinev, and new information on the reactor antineutrino energy spectra important for data analysis were presented by V. Kopeikin.

We consider the oscillation experiments at reactors as an effective tool to investigate the internal mass-structure of the electron neutrino. To this end we use the analysis developed in [5].

All oscillation experiments considered here are based on the reaction of the inverse beta decay

$$\bar{\nu} + p \rightarrow n + e^{+} \tag{1}$$

with a threshold of 1.80 MeV, and use (e^+, n) delay coincidence technique. The energy of the ejected positron is

$$T = E - 1.80 \text{ MeV} \tag{1'}$$

(E is the energy of the incoming antineutrino). In most cases the annihilation quanta are absorbed in the fiducial volume and the visible energy of positron is $\sim$1 MeV higher than the one given above. The first two experiments make use of Gd loaded liquid scintillator as a $\bar{\nu_e}$ target, for Kr2Det and very long baseline experiments Gd is not planned.

1. MOTIVATIONS

1.1. First consider the oscillation process in the two-neutrino model. The survival probability $P(\bar{\nu_e} \to \bar{\nu_e})$ that the electron antineutrino will retain its initial flavor at a distance of L meters from the source is given by the expression:

$$P(\bar{\nu_e} \to \bar{\nu_e}) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \tag{2}$$

where $\sin^2 2\theta$ is the mixing parameter; $\Delta m^2(\text{eV}^2) \equiv m_2^2 - m_1^2$ is the mass parameter and $m_{1,2}$ are the neutrino eigenmasses.

A specific deformation of the measured positron (antineutrino) energy spectrum and a deficit of the total antineutrino detection rate relative to the no-oscillation case are the oscillation signatures, which are searched for in the experiment. Calculation shows that for soft reactor neutrinos the distortion of the energy spectrum is most pronounced and the deficit of the neutrino detection rate is maximal for

$$\Delta m^2 L \approx 5 \ (\text{eV}^2 m) \qquad (\text{sensitivity condition}). \tag{3}$$

1.2. There is no theory which can predict today neutrino mass and mixing parameters. Positive information on this subject comes from the studies of the atmospheric and solar neutrinos. The Super-Kamiokande observations of atmospheric neutrinos provide a strong evidence for neutrino oscillations. Recent data reported at NEUTRINO'2000, if interpreted as $\nu_\mu \leftrightarrow \nu_\tau$ transitions, are best fit by the oscillation parameters [6]:

$$\Delta m^2_{\text{atm}} \approx 3 \cdot 10^{-3} \text{ eV}^2 \ (\text{most probable value}), \ \sin^2 2\theta_{\text{atm}} > 0.88. \tag{4}$$

It should be emphasized however that the analysis of the atmospheric neutrinos leaves quite a large room for the $\nu_\mu \leftrightarrow \nu_e$ channel as a subdominant one.

The energy dependent deficit of the solar neutrinos relative to the Standard Solar Model prediction is another strong argument in favor of the oscillation hypothesis. By assigning particular values to the parameters Δm^2 and $\sin^2 2\theta$ and by inclusion of the MSW mechanism all observations can be accounted for [7]. The most recent data from Super-Kamiokande as analyzed in [8] give however a strong preference to only one of the solutions labeled as Large Mixing Angle (LMA) MSW solution:

$$\Delta m^2_{\text{sol}} \approx 3 \cdot 10^{-5} \text{ eV}^2, \qquad \sin^2 2\theta_{\text{sol}} \approx 0.7. \tag{5}$$

Other possibilities, the SMA MSW and vacuum oscillation solutions, are now strongly disfavored.

Equations (3)–(5) show that the long baseline (LBL) and very long baseline (VLBL) reactor experiments explore the electron neutrino mixing in the atmospheric and solar neutrino mass parameter regions, respectively.

1.3. Consider the three active neutrino oscillations. In this case the mixing parameters $\sin^2 2\theta$ are expressed through the elements of the neutrino mixing matrix U_{ei}, which represent the contributions of the mass states (ν_i are the mass eigenstates) to the electron neutrino flavor state ν_e:

$$\begin{gathered}\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3 \quad \text{with} \quad U_{e1}^2 + U_{e2}^2 + U_{e3}^2 = 1; \\ \sin^2 2\theta_{\mathrm{LBL}} = 4U_{e3}^2(1 - U_{e3}^2), \\ \sin^2 2\theta_{\mathrm{VLBL}} = 4U_{e1}^2 U_{e2}^2.\end{gathered} \tag{6}$$

We conclude that the LBL and VLBL experiments at reactors can provide full information on the electron neutrino mass structure, at least in the 3-neutrino mixing model. It is interesting to mention that sensitive measurements of U_{e3} can help to choose between possible oscillation solutions of the solar neutrino problem independent of the VLBL experiments [9].

2. THE CHOOZ EXPERIMENT

The CHOOZ detector was built in an underground gallery (300 mwe) at distances of about 1000 m and 1110 m from two RWR reactors of total nominal power 8.5 GW (th). The detector shown in Fig. 1 has three concentric zones. The central zone with 5 tons of hydrogen-rich Gd-loaded liquid scintillator served as a target for antineutrinos. The target is immersed in a 70 cm thick intermediate zone filled with a Gd-free scintillator (17 tons) and surrounded by a veto outer region with 90 tons of ordinary scintillator. The inner two zones are viewed by 192 eight-inch PMT's.

The data was obtained at different power levels of the CHOOZ NPP newly built reactors as they were gradually brought into operation. This schedule was very useful for determining the reactor OFF background. A summary of data taking periods from April 1997 till July 1998 is shown in Table 1.

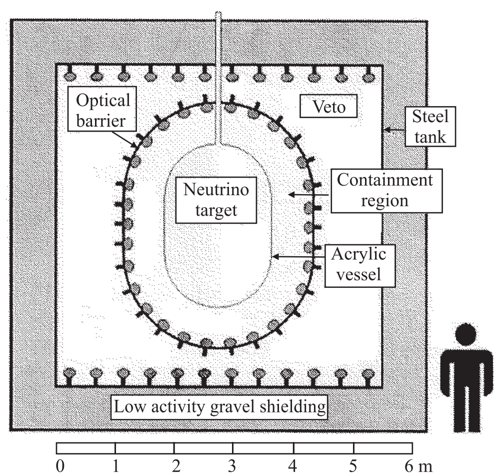

Fig. 1. The CHOOZ detector

The selection of neutrino events is based on the following conditions: (i) energy cuts on the positron candidate (1.3–8 MeV) and on the neutron candidate (6–12 MeV), (ii) a time window on the delay between e^+ and neutron (2–100 ms), (iii) spatial cuts on the positron and neutron positions (the distance from the PMT surface > 0.3 m and the distance between

Table 1. **CHOOZ data acquisition periods**

	Time, d	W, GW
Reactor 1 ON	85.7	4.03
Reactor 2 ON	49.5	3.48
Reactor 1 and 2 ON	64.3	5.72
Reactor 1 and 2 OFF	142.5	—

positron and neutron events < 1.0 m). Under these conditions the antineutrino detection efficiency was found to be $\epsilon = (69.8 \pm 1.1)\%$.

Total about 2500 $\bar{\nu}_e$ were detected during the data acquisition periods. The measured neutrino detection rate is 2.58 per day per GW of reactor power and the typical ratio of the neutrino to background detection rates is 10:1. The ratio $R_{\text{meas/calc}}$ of the measured to expected for no-oscillation case neutrino detection rates is found to be:

$$R_{\text{meas/calc}} = 1.01 \pm 2.8\,\% \text{ (stat.)} \pm 2.7\,\% \text{ (syst.)}. \tag{7}$$

Ratio (7) was computed with the use of the reaction (1) cross section accurately measured by the Kurchatov-IN2P3 group at a distance of 15 m from the Bugey-5 reactor [10]. Uncertainties which build up the total systematic error given in (7) are listed in Table 2.

Table 2. **Components of the CHOOZ 68 % CL systematic uncertainties**

Parameter	Relative error, %
Reaction cross section	1.9
Number of protons	0.8
Detection efficiency	1.4
Reactor power	0.7
Energy absorbed per fission	0.6
Combined	2.7

The positron and background spectra measured during reactor ON and OFF periods are shown in Fig. 2, *a*, the ratio of the measured to the expected spectrum can be seen in Fig. 2, *b*. Clearly, neither the $\bar{\nu}_e$ detection rate, nor positron spectrum shows any signs of neutrino oscillation.

The CHOOZ oscillation constraints are derived by comparing all the available experimental information to expected no-oscillation values. The result (Fig. 3, the curve «CHOOZ») directly depends on the correct determination of the absolute $\bar{\nu}_e$ flux and their energy spectra, the nuclear fuel burn up effects, $\bar{\nu}_e$ cross section, detector efficiency and spectral response. We note that CHOOZ does not observe the $\bar{\nu}_e$ oscillation in the mass region Δm^2_{atm} where muon neutrinos oscillate intensively:

$$\sin^2 2\theta_{\text{CHOOZ}} \leq 0.1, \qquad U^2_{e3} \leq 2.5 \cdot 10^{-2} \quad \text{at } \Delta m^2 = 3 \cdot 10^{-3} \text{ eV}^2. \tag{8}$$

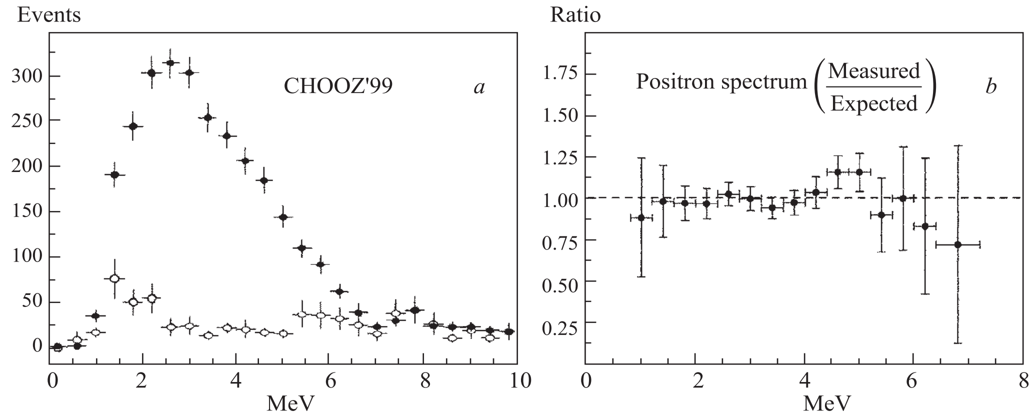

Fig. 2. CHOOZ positron energy spectrum: *a*) spectra in reactor ON and OFF periods; *b*) measured to expected no-oscillation ratio

The CHOOZ experiment has demonstrated a considerable improvement on the reactor $\bar{\nu}_e$ detection techniques: the level of the background at CHOOZ ($\sim$ 0.3 per day, per 1 ton of a target) is almost a thousand times lower than the one ever achieved in previous experiments. In this connection we would mention two important points. The first is the underground position of the detector. The 300 mwe rock overburden reduces the flux of cosmic muons, the main source of the time-correlated background, by a factor of $\sim$ 300 to a value of 0.4 $\mathrm{m^{-2} \cdot s^{-1}}$. The second point is associated with the zone-2 of the detector. The scintillator of this zone absorbs the radiation coming from high natural radioactivity of the PMT's glass and relevant events are rejected by the spatial cuts thus reducing the accidentals. These two features are specific for future LBL and VLBL projects with the difference that greater baselines require deeper detector positions and the protective region between the fiducial volume and PMTs is thicker and is filled with nonscintillating mineral oil.

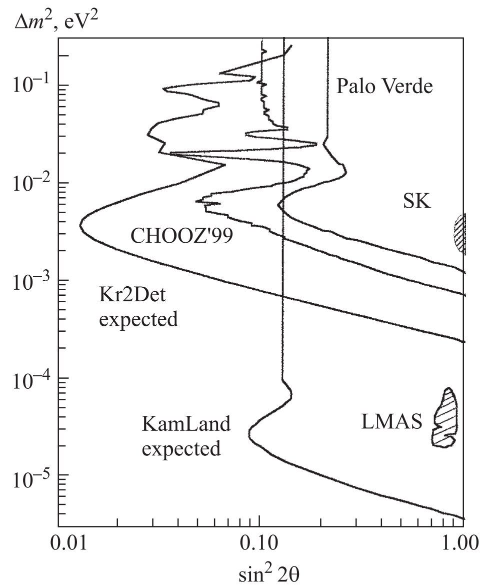

Fig. 3. Reactor neutrino (90 % C.L.) oscillation limits. The shaded areas are the atmospheric and solar neutrino allowed oscillation regions

3. THE PALO VERDE EXPERIMENT

This experiment uses detector of quite a different design and more sophisticated selection criteria. The difference is caused by a shallow position of the laboratory (32 mwe) and $\sim$ 50 times higher muon flux than at the CHOOZ site.

The $\bar{\nu}_e$ target is a 6×11 matrix composed of $12.7 \times 25 \times 900$ cm acrylic cells. The inner 7.4 m-long part of the sell is active and 0.8 m on each side serve as oil light guides and buffers, which shield the central part from external radioactivity (Fig. 4). The total volume of the liquid scintillator (Gd) amounts to 12 m^3. A 1m-thick layer of purified water passive shielding surrounds the central detector. The outmost layer of the detector is composed of veto counters. The veto rate is typically $\sim$ 2 kHz. The experiment is situated in Arizona (the USA). Three identical PWR type reactors of total power of 11.6 GW (th) are located at distances of 890, 890 and 750 m from the detector. Each reactor is shut down for refueling every year. Two of the reactors are ON at any given time.

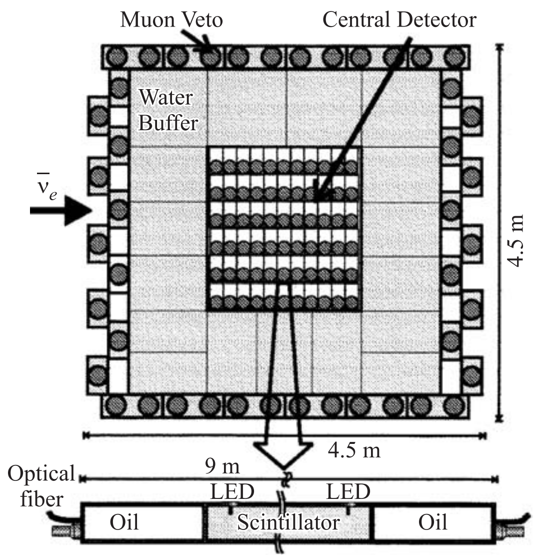

Fig. 4. The Palo Verde detector

The positron trigger is a fast (30 ns) triple coincidence between neighboring cells requiring one cell above 600 keV (positron ionization) and two cells above $\sim$ 40 keV to detect Compton recoils from annihilation quanta. Similar conditions are used for the neutron candidates. The time delay between the positron and neutron «triples» was chosen about 450 ms long, much longer than neutron capture time in the Gd-loaded scintillator ($\sim$ 30 ms), which was useful for determining the accidental coincidence background. For details of subsequent cuts applied in the offline data treating we refer to [2].

Presently the results based on data taking period from July 1998 to September 1999 are available. In 1998 one of the reactors at 890 m was OFF for 31 days and in 1999 the reactor at 750 m was OFF for about 23 days. The three reactors ON minus two reactors ON give the following neutrino detection rates (per day):

$$6.0 \pm 1.4 \text{ (stat.) in 1998 and } \quad 9.0 \pm 1.6 \text{ (stat.) in 1999.} \tag{9}$$

The neutrino detection efficiencies are estimated as 7.6 % (1998) and 11 % (1999). The rates are found to be compatible with no-oscillation predictions.

The ON-OFF method treats the $\bar{\nu}_e$ flux from the two reactors still at full power as background, which considerably reduces the statistical accuracy of the results. An independent analysis named the «swap» method is based on (i) the symmetry of the most of the backgrounds relative to the exchange of the first and the second subevents and on (ii) the strong asymmetry of the positron and delayed neutron signals. The «swap» analysis uses full neutrino statistics. It makes it possible to cancel most of the background directly from the data. The remaining part is computed using Monte Carlo simulations. The ratio $R_{\text{meas/calc}}$ of the measured to expected for no-oscillation case neutrino detection rates found by means of the «swap» method is:

$$R_{\text{meas/calc}} = 1.04 \pm 3\,\% \text{ (stat.)} \pm 8\,\% \text{ (syst.)}. \tag{10}$$

Clearly the gain in statistic relative to the classic ON-OFF method (see (9)) is quite impressive. The systematic uncertainties are summarized in Table 3. The best of the Palo Verde oscillation exclusion plot is shown in Fig. 3.

Table 3. **The Palo Verde systematic uncertainties [2]**

Error source	ON minus OFF, %	Swap, %
e^+ efficiency	4	4
n efficiency	3	3
Neutrino flux prediction	3	3
Neutrino selection cuts	8	4
BKG estimate	—	6
Total	10	8

4. THE KRASNOYARSK: TWO-DETECTOR PROJECT Kr2Det

The Kr2Det (about 1 km baseline project) is aimed at more sensitive searches for neutrino oscillations in the mass parameter region already studied in the CHOOZ and Palo Verde experiments. The physical goals of the project are: (i) to obtain new information on the electron neutrino mass structure (U_{e3}), (ii) to provide a better normalization for future accelerator neutrino experiments, and (iii) to achieve better understanding of the atmospheric neutrinos. It is also worth mentioning that just in case the LMA solution is valid, U_{e3} can be quite close to the presently available CHOOZ upper limit $U_{e3}^2 \le 2.5 \cdot 10^{-2}$ while for the SMA MSW and vacuum oscillation solutions the predicted value of U_{e3} is much smaller [9]. The project intends:

- to increase, relative to CHOOZ, the sample of detected neutrinos by a factor of 20. The Kr2Det neutrino target mass is 50 tons, ten times larger than used in the CHOOZ experiment;
- to eliminate most of the systematic uncertainties by using two identically designed scintillation spectrometer (far and near) stationed at 1100 and 250 m from the reactor;
- to use special calibrations to control and correct for systematic uncertainties that will still remain.

The detectors are installed at a depth of 600 mwe with the flux of cosmic muons there 5 times lower than at the CHOOZ laboratory, which helps to keep the backgrounds at sufficiently low level.

Each of the detectors (Fig. 5) has a three-concentric zone design: the 50-ton liquid scintillator (without Gd) target in the centre, the buffer of nonscintillating oil and the outer veto zone. Expected neutrino detection and background rates are: $N_\nu = 50\ \text{d}^{-1}$, $N_{\text{BKG}} = 5\ \text{d}^{-1}$.

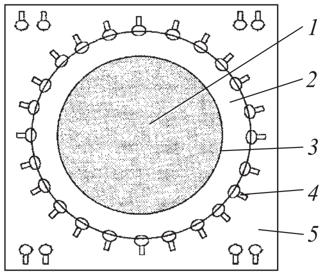

Fig. 5. The Kr2Det detector: *1* — the neutrino target (50 ton mineral oil + PPO); *2* — mineral oil; *3* — the transparent film; *4* — the PMTs; *5* — veto zone

In the no-oscillation case the ratio of the two simultaneously measured positron spectra does not depend on the positron energy, small deviation from the constant value is analyzed for the oscillation parameters. The results of this purely relative analysis are independent of the exact knowledge of reactor power and the fuel burn up effects, of numbers of target protons and detection efficiencies. Calibration of the detectors is a key problem of the experiment. More details on calibration procedures are considered in [2]. Expected 90 % C.L. oscillation limits are presented in Fig. 3. It was assumed that 40 thousand $\bar{\nu_e}$ are detected and that systematics is controlled down to a 0.5 % level.

5. KamLAND

The KamLAND detector will operate in the Kamiokande detector cave with a rock overburden of 2700 mwe. The neutrinos originate from 16 NPP (total 51 power reactors) at distances of 80–820 km. 80 % of the total $\bar{\nu_e}$ flux comes from reactors between 140 and 210 km away.

Table 4. **Some parameters of the underground oscillation experiments at reactors**

Parameter	L, km	mwe	Target mass, t	N_ν, $t^{-1} \cdot y^{-1}$	$N_{\rm BKG}$, $t^{-1} \cdot y^{-1}$
CHOOZ	1.1	300	5	900	90
Kr2Det*	1.1	600	50	370	40**
KamLAND	~200	2700	1000	0.8	0.08**

* Detector in the 1100 m position.
** Estimated values.

The reactor neutrino flux on the target is extremely small, 1000 times smaller than in the CHOOZ experiment, while the muon flux at this depth is attenuated only by a factor of ~ 400 with respect to the value at the CHOOZ laboratory. Thus the background problems are of primary importance.

The KamLAND detector again has three concentric zones (Fig. 6). The 13 m-diameter target zone with 1000 tons of purified scintillator is in the centre. A 1700-ton buffer is filled with mineral oil and this time is 2.5 m thick. The scintillator is viewed by an array of 2000 photomultipliers supported on a 19 m-diameter steel sphere. The zone-3 outside the steel sphere is filled with purified water and serves as a Cherencov veto detector and additional passive shielding.

The calculated average neutrino detection rate is about 750 per year and is expected to vary by $\sim \pm 10\,\%$ due to the seasonal variation of the nuclear power production. Clearly the ON–OFF approach does not seem promising in this case. On the other hand the correlated background rates are estimated as low as about 20 events per year and the expected oscillation effect for LMA solar solution is quite large.

The derived sensitivity to the oscillation parameters assuming three years of data taking and the neutrino oscillations to background ratio 10:1 is shown in Fig. 3. It can be seen that the LMA solution can be conclusively tested.

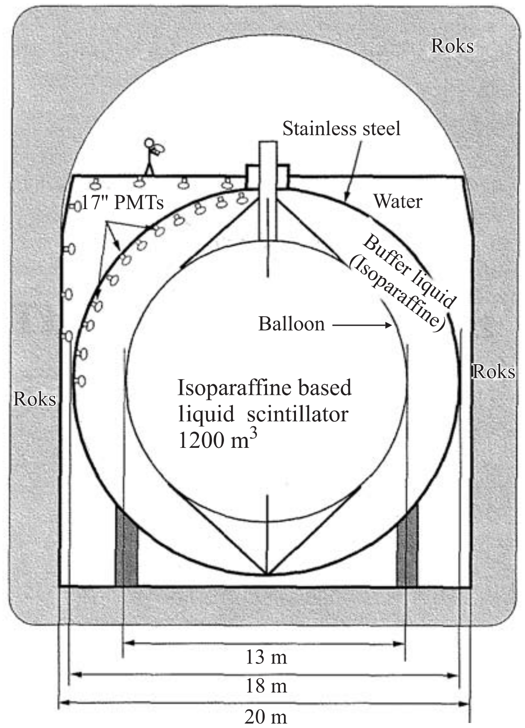

Fig. 6. The KamLAND detector

6. SUMMARY AND CONCLUSIONS

The 1km-baseline CHOOZ and, with a small delay, Palo Verde are the first of the terrestrial neutrino oscillation experiments that have successfully explored the atmospheric mass parameter region. The negative result of these experiments has an important positive meaning that the electron neutrino contains not much admixture of the third neutrino mass eigenstate.

The success of the CHOOZ experiment is based on impressive (almost three orders of magnitude) improvements on the reactor neutrino detection technique. A revolutionary progress in the field is well underway as can be seen from Table 4, which summarizes some parameters of the experiments discussed in this report.

More sensitive searches for the admixture of the third neutrino mass eigenstate are feasible now (Kr2Det). An invasion into the LMA MSW solar region (KamLAND) requires another three orders of magnitude reduction of the backgrounds, which most probably can be achieved. We conclude that, with reactor experiments, in a few years the electron neutrino mass structure can be understood and a decisive proof of the solar neutrino problem found.

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