NEUTRINO PHYSICS AFTER KAMLAND

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The neutrino anomalies were driving force of the developments in neutrino physics during the last 30 - 35 years. I will consider status of the anomalies after the first KamLAND result. The main questions are “What is left?” and “What is the next?” In the new phase, the phenomenological objectives of neutrino physics consist of accomplishing the program of reconstruction of the neutrino mass and flavor spectrum and searches for physics beyond the “standard” picture. The latter includes searches for new (sterile) neutrino states, new neutrino interactions, effects of violation of the fundamental symmetries in the neutrino sector.

1. Introduction

1.1. Before and After

“After KamLAND” means essentially after confirmation of the large mixing MSW (LMA) solution of the solar neutrino problem. In this sense, neutrino physics “after KamLAND” has started much before the announcement of the first KamLAND result 1. Since 1999 most of the papers (on theoretical implications and phenomenology including physics of the long-base line experiments) has been written in the context of LMA solution.

1998 was the turn point. The essence of “Revolution-98” inspired by the SuperKamiokande results on the atmospheric 2 and solar 3 neutrinos consisted of

- strong evidence of the $\nu_\mu - \nu_\tau$ oscillations of the atmospheric neutrinos with maximal or nearly maximal mixing,
- strong evidence against the small mixing MSW solution of the solar neutrino problem.

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The prejudice of small mixing, which was the dominating idea during many years, has been destroyed.

Already in 1998, the solar neutrino data gave some hint that the large mixing MSW effect can be the solution of the solar neutrino problem. With more data appeared, LMA became favored and then the most plausible explanation. On the basis of LMA, detailed predictions for KamLAND have been done.

The KamLAND result is the culmination of about 40 years of the solar neutrino studies. This result is the confirmation of not only LMA (in assumption of the CPT symmetry), but also the whole oscillation picture behind the neutrino anomalies including the oscillations of atmospheric neutrinos.

1.2. The end of era of the neutrino anomalies?

Neutrino anomalies, both real and fake, were driving force of developments in the field. The famous triplet is solar-atmospheric-LSND. The atmospheric neutrino anomaly and the solar neutrino problem turned out to be real (not related to experimental or systematic errors), confirmed and practically resolved. The LSND anomaly is badly resolved, not confirmed, but not yet excluded.

Fake anomalies played certain positive role attracting the interest to the field, forcing to think and ... invent sometimes correct theoretical ideas (e.g. neutrino oscillations). The list includes the 17 eV (ITEP) mass, 17 kev neutrino, BUGEY oscillations, KARMEN anomaly, Troitzk anomaly, etc.

There are some problems in physics and astrophysics which may be related to neutrinos: Ultra-high energy cosmic rays beyond the GZK limit, nucleosynthesis of heavy elements, large pulsar kicks, etc.

The main questions now are “What is left?” and “What is the next?”

2. Is the solar neutrino problem solved?

2.1. Solar neutrinos and KamLAND

The first KamLAND result (see analysis in and fig. 1 from)

- has confirmed (in assumption of CPT) the LMA MSW solution and excluded other suggested effects at least as the dominant mechanisms.
- has further shifted the allowed region and the best fit point to larger
values of $\Delta m^2$:
\[
\Delta m^2 = (5 \rightarrow 7) \cdot 10^{-5} \text{ eV}^2, \quad (1)
\]
- put the lower bound on $\Delta m^2$
\[
\Delta m^2 > (4 - 5) \cdot 10^{-5} \text{ eV}^2, \quad (2)
\]
which looks rather solid: for smaller $\Delta m^2$ the strong distortion of the spectrum is predicted which contradicts the data.

In fig. 1 I show the allowed regions of oscillation parameters from the combined analysis of the solar neutrino data and KamLAND data. Clearly, there is no enough sensitivity to $s_{13}$ at present.

2.2. **LMA: precision measurements**

Further decrease of the allowed $\Delta m^2 - \tan^2 \theta$ region is needed for a number of reasons: for theoretical implications, further phenomenological and experimental developments, and also for precise understanding the physical picture of neutrino conversion. Indeed, high values of $\Delta m^2$ correspond to
vacuum oscillations with small matter corrections. Low values of $\Delta m^2$ - to the non-oscillatory adiabatic conversion (for $E > 5$ MeV). Small mixing admits clear resonance description. Maximal mixing means that the resonance is at zero density.

The forthcoming improvements are expected from further operation of SNO and KamLAND. In the fig. 2 we show the contours of constant ratio CC/NC and Day-Night asymmetry in the plane of oscillation parameters. The expected accuracy of the measurements of CC/NC is about 10%, so that the two regions (h- higher and l - lower) can be distinguished. In the range $\Delta m^2 < 10^{-4} \text{ eV}^2$, SNO will give preciser determination of the mixing angle and more stringent bound on the deviation from maximal mixing. Later KamLAND will achieve 10% accuracy in $\Delta m^2$. This accuracy is comparable with a possible effect of $s_{13}$.

In future the analysis of data will be performed in two stages:

1) Identification of the unique region (discrimination between LMA-h and LMA-l). At this stage the analysis of data can be performed in the context of two neutrino mixing and the sub-leading effects due to the 1-3 mixing can be neglected.

Figure 2. The allowed 1σ and 3σ regions (shadowed) of oscillation parameters from the combined analysis of the solar neutrino data and KamLAND. Shown are also contours of the constant Day-Night asymmetry (dotted lines) and the CC/NC ratio (dashed lines). From 8.
2). Precision measurements. Possible sub-leading effects should be included. The generic 3ν- analysis should be performed. Problem of degeneracy of parameters will appear.

2.3. Consistency checks

Till now no a single signature of the LMA solution (e.g., the day-night asymmetry, upturn of the spectrum) has been observed at a statistically significant level. What is expected? The following predictions correspond to the present best fit region:

- the Day-Night asymmetry at SNO and SK:
  \[ A_{DN}(SNO) = (2 - 5)\%, \quad A_{DN}(SK) = (1 - 3)\% \]

- spectrum distortion: the 5 - 10 % upturn is expected at low energies between 8 and 5 MeV,

- suppression of the signal at the intermediate energies (BOREXINO and KamLAND):
  \[ R_B = (0.6 - 0.65)R_B^{SSM}, \]

  (where the effect of the NC interactions for ν - e scattering has been taken into account).

- small seasonal variations: the expected winter-summer asymmetry of the signal at SNO and SK, \( A_{WS} < 0.5\% \), is practically unobservable,

- suppression of the \( pp \)- neutrino flux: \( R_{pp} = 0.6 \) which can be measured in future low energy solar neutrino experiments.

Tests of these predictions have the threefold implication: (i) further confirmation of LMA: one needs to over determine the solution to perform its cross-checks; (ii) precise determination of the neutrino parameters; (iii) searches for physics “Beyond LMA”.

2.4. Homestake anomaly?

Quality of description of the available data by the LMA solution is very good: according to the global fit \( \chi^2/d.o.f. = 68.2/91 \). This is also confirmed by the pull-of diagram. A visible deviation appears in one place only: LMA predicts about \( \sim 2\sigma \) higher Ar-production rate as compared with the Homestake result.

Possible interpretation? (i) the statistical fluctuation; (ii) unknown systematics, probably related to the claimed time variations of the Homestake
signal (in some periods of time the efficiency of detection was lower); (iii) neutrino physics beyond LMA.

The latter can be related to another observation: the absence of apparent upturn of the spectrum (ratio of the observed spectrum to the SSM prediction) at low energies. Neither SK nor SNO see any upturn, though the sensitivity may not be enough.

Both the lower Ar-production rate and the absence (suppression) of the upturn can be due to the effect of additional (sterile) neutrino which mixes very weakly with active neutrinos (mainly, $\nu_s - \nu_1$) and has small mass split with the lightest state $\nu_1$:

$$\sin^2 2\theta_{s1} = (10^{-4} - 10^{-3}), \quad \Delta m_{01}^2 = (0.5 - 1) \cdot 10^{-5} \text{eV}^2.$$ (5)

Such a neutrino produces an additional dip in the suppression pit in the range 0.8 - 5 MeV, thus suppressing the Be-neutrino line or/and the upturn of spectrum. BOREXINO and KamLAND can check this.

2.5. Solar neutrinos versus KamLAND

From the 2$\nu$ analysis of the solar neutrino data and independent 2$\nu$ analysis of the KamLAND results one finds that values of parameters in the best fit points coincide

$$(\Delta m^2, \tan^2 \theta)_{solar} \approx (\Delta m^2, \tan^2 \theta)_{KamLAND}$$ (6)

within 1$\sigma$. This indicates that CPT is conserved in the leptonic sector.

It is interesting to further check the equality with increasing accuracy. The mismatch of parameters can testify for the CPT violation or, more probably, for certain physics beyond LMA.

If some effect influences the KamLAND signal it should also show up in the solar neutrinos. Inverse is not true: a number of effects can influence the solar neutrinos but not KamLAND. The solar neutrinos have much higher sensitivity to physics beyond LMA than KamLAND. Some examples: an additional neutrino state with small $\Delta m^2$ or/and $\tan^2 \theta$, the neutrino spin-flip in the Sun, non-standard interactions of neutrinos.

There is another interesting aspect of comparison of the oscillation parameters extracted from the solar neutrinos and KamLAND, namely, - a test of theory of the conversion and oscillations. Indeed, physics behind the solar neutrino conversion and the oscillations of reactor neutrinos is different. In the case of solar neutrinos we deal with the adiabatic conversion; the matter effect dominates (at least in the high energy part of the spectrum), the oscillation phase is irrelevant. The effect is described by the
adiabatic conversion formula. In contrast, in the case of KamLAND, the vacuum oscillations occur; the matter effect is very small; the oscillation phase is crucial. Here we use the vacuum oscillation formula.

The coincidence of parameters (6) testifies for correctness of the theory (phase of oscillations, matter potential, etc.), see also discussion in 9.

2.6. Beyond LMA or Physics of sub-leading effects

The physics of sub-leading effects becomes one of the main subjects of studies. The name of the game is “LMA + something”, where LMA provides the leading effect, and “something” can be $U_{e3}$, SFP (spin-flavor precession), new neutrino states, NSI (non-standard interactions), VEP (violation of the equivalence principle), etc. The implications of these studies include the neutrino properties (e.g., magnetic moments), physics beyond the Standard Model, characteristics of the interior of the Sun.

“LMA + sterile neutrinos”: the signatures are the modification of the CC/NC ratio and additional distortion of the energy spectrum. An example has been described in sect. 2.4.

“LMA + NSI”: an additional contribution to the matter effect appears; some deviations from usual relations between $\Delta m^2$ and $\tan^2 \theta$ are expected. Some work in this direction has already been performed before KamLAND announcement 10, 9.

In what follows we will comment on the “LMA + SFP” scenario. If no new neutrino states exist, the only relevant mass difference is $\Delta m^2_{LMA}$. For such a large $\Delta m^2$ the spin-flip occurs in the central regions of the sun (radiative zone) where the potential $V \sim \Delta m^2_{LMA}/2E$. The signature of the scenario is the appearance of the antineutrino flux. For the Boron neutrinos the ratio of $\bar{\nu}_e$ flux to the original $\nu_e$ flux equals

$$\frac{\bar{F}_B}{F_B} = 1.5\% \left( \frac{\mu_\nu}{10^{-12} \mu_B} \right)^2 \left( \frac{B}{100 \text{MG}} \right)^2,$$

(7)

where $\mu_\nu$ is the magnetic moment of neutrino, $\mu_B$ is the Bohr magneton. For $B = 7$ MG, that is, at the level of present upper bounds $^{12}$ and $\mu_\nu = 10^{-12} \mu_B$ we get $\bar{F}_B/F_B = 7 \cdot 10^{-3}\%$, which is 2 orders of magnitude below the present limit $^{13}$.

Unless Voloshin’s cancellation $^{14}$ or polarization suppression $^{15}$ in the mass term $m_\nu$ occurs, the relation exists

$$\mu_\nu \sim \frac{e}{\Lambda^2} m_\nu,$$

(8)
where $e$ is the electric charge and $\Lambda$ is the energy scale (energy cut) at which
the magnetic moment is formed. For $\Lambda = 100$ GeV and $m_\nu = 1$ eV we find
$\mu_\nu = 10^{-16} \mu_B$ which is practically unobservable. In particular, according
to (7) the antineutrino flux is smaller than $10^{-8}\%$.

The spin-flip effect can be much larger, if new neutrino states exist with
$\Delta m^2 \ll \Delta m^2_{LMA}$.

2.7. Solar neutrino astrophysics

After resolution of the solar neutrino problem we can come back to the
original task: the spectroscopy of solar neutrinos for studies of interior
properties of the Sun, that is, neutrino diagnostics of the Sun. This
program includes determination of the original neutrino fluxes, in particu-
lar, neutrino fluxes from the pp- and CNO cycles and searches for time
variations of fluxes.

Interesting to note that the original $\nu_e$ fluxes as they appear in the SSM
do not exist in nature! According to LMA, the flavor conversion/oscillations
starts already in the neutrino production region. Still we can introduce
these fluxes since there is no back influence of the neutrino conversion on
the solar characteristics and production of neutrinos. Conversion effects
can be subtracted. In any case we can speak on the total flux without
specification of flavor.

3. Atmospheric neutrinos: Any problem?

There is a compelling evidence that the $\nu_\mu - \nu_\tau$ vacuum oscillations are the
dominant mechanism of the atmospheric neutrino transformations. This
evidence is provided by SuperKamiokande, MACRO, SOUDAN. It is confirmed by K2K.
Nothing statistically significant beyond this interpretation has been found so far. Though there is, probably, some
tension between the observed up-down asymmetry of the $\mu$-like events and
the ratio of total numbers of the $\mu$-like and $e$-like events. Also situation
with the original neutrino fluxes is not yet clear. Eventually this may
lead to some change of the extracted values of oscillation parameters or to
discovery of some new sub-leading effects, but it will hardly influence the
whole oscillation interpretation.

What is the next? As in the case of solar neutrinos: the next is physics
of the sub-leading effects and also geo- and cosmo- physics. Among objectives are searches for (i) the $\nu_e$ and $\bar{\nu}_e$ oscillations, (ii) effects of $s_{13}$, (iii)
sterile neutrinos, (iv) CP-violation, (v) CPT-violation, (vi) specific oscilla-
tion effects related to the earth density profile (parametric enhancement of oscillations for core - mantle crossing trajectories), etc.

Precision measurements of the atmospheric neutrino fluxes can be used for studies of the cosmic ray fluxes once oscillation effects are well understood.

3.1. Oscillations of Atmospheric $\nu_e$

After KamLAND we can say that even for $s_{13} = 0$ the $\nu_e$-, $\bar{\nu}_e$- oscillation effects must appear at some level due to the solar/KamLAND oscillation parameters. The signature of these oscillations is an excess (or deficit) of the $e$-like events in certain energy range with specific energy and zenith angle dependences.

The $e$-like event excess (deficit) can be due to

(i). oscillations driven by the solar $\Delta m_{12}^2$, $\theta_{12}$, (mainly in the sub-GeV region),

(ii). oscillations driven by nonzero $\theta_{13}$ and atmospheric $\Delta m_{13}^2$ (mainly in the multi-GeV region),

(iii). interference of the above effects.

We will consider these possibilities in order.

3.2. Oscillations due to $\Delta m_{12}^2$, $\theta_{12}$

A relative change of the $\nu_e$- flux due to the oscillations equals

$$\frac{F_e}{F_{e0}} - 1 = P_2(r \cos^2 \theta_{23} - 1),$$

where $P_2 = P(\Delta m_{12}^2, \theta_{12})$ is the $2\nu$ transition probability $\nu_e \rightarrow \nu_{\mu,\tau}$ in the matter of the Earth, and $r \equiv F_0^\mu/F_e^0$. The effect is strongly suppressed by the “screening factor” (in the brackets of (9)) in spite of large transition probability, $P_2$. Indeed, in the sub-GeV region $r \approx 2$ and the oscillation effect is zero for the maximal 2-3 mixing. This feature can be used to search for deviations of the 2-3 mixing from the maximal one. The excess (deficit) of the events is directly proportional to this deviation. In the Table we show the excess

$$\epsilon \equiv \frac{N_e}{N_{e0}} - 1$$

in the sub-GeV region for different values of $\sin^2 2\theta_{23}$ and for the best fit points of the LMA-l and LMA-h regions. The excess increases with $\Delta m_{12}^2$, but does not exceed 5%. Once the LMA parameters are well known, measurements of $\epsilon$ will allow to restrict a deviation of the 2-3 mixing from the
maximal one. To realize this one needs high statistics experiment and a possibility to identify the excess due to oscillations (in particular, distinguish it from uncertainties in the normalization of the original flux).

3.3. Effect of $s_{13}$

The oscillations driven by non-zero $s_{13}$ and the atmospheric $\Delta m^2_{13}$ produce significant modification of the $\nu_e$ flux in the multi-GeV region, where the oscillations are enhanced by the matter effects (MSW resonances in the mantle and core, the parametric enhancement of oscillations). In contrast to the sub-GeV sample, at higher energies $r$ significantly deviates from 2 and the screening $\propto (r \sin^2 \theta_{23} - 1)$ is weaker. The oscillation effect can be identified by the up-down asymmetry:

$$A_{U/D} = 2 \frac{U - D}{U + D},$$

where $U$ and $D$ are the numbers of $e$-like events in the intervals of zenith angles $\cos \Theta = (-1 \div -0.6)$ and $\cos \Theta = (0.6 \div 1)$ correspondingly. For $\sin^2 2\theta_{23} = 1$ and $\Delta m^2_{13} = (2 - 3) \cdot 10^{-3} \text{eV}^2$ the asymmetry in the multi-GeV region can reach $(5 - 8)\%$ for the maximally allowed 1-3 mixing.

3.4. Induced interference

If $s_{13} \neq 0$ the interference of effects produced by the solar oscillation parameters and $s_{13}$ should be taken into account. In the sub-GeV range, the non-zero $s_{13}$ induces the interference of the survival, $A_{ee}$, and transition, $A_{e\mu}$, amplitudes of the $2\nu$ system with $\Delta m^2_{12}$ and $\theta_{12}$. The relative change of the $\nu_e$ flux can be written as

$$\frac{F_e}{F^0_e} = 1 - P_2(r \cos^2 \theta_{23} - 1) -$$

$$rs_{13} \sin 2\theta_{23} Re(A_{ee}^* A_{e\mu}) -$$

$$s^2_{13}[2(1 - r \sin^2 \theta_{23}) + P_2(r - 2)],$$

where $P_2 \equiv |A_{e\mu}|^2$. The interference effect given by the second term in the RH side of (12) has the following properties: (i) it is linear in $s_{13}$, (ii) has

| $\sin^2 2\theta_{23}$ | $\epsilon_1$, % | $\epsilon_h$, % |
|---------------------|-------------|-------------|
| 0.91                | 2.8         | 4.8         |
| 0.96                | 1.9         | 3.2         |
| 0.99                | 0.9         | 1.6         |
no screening factor, (iii) has opposite signs for neutrinos and antineutrinos, (iv) maximal for $\Delta m_{12}^2 = 7 \cdot 10^{-5} \text{ eV}^2$. In fig. 3 from 25 we show the zenith angle distributions of the $e$-like events for different values of mixing.

![Figure 3](image_url)

**Figure 3.** The zenith angle distributions of the $e$-like events (ratio of number of events with, $N_{e}$, and without, $N_{0e}$, oscillations) in the sub-GeV range ($p < 0.4 \text{ GeV}$) for $\Delta m_{12} = 5 \cdot 10^{-5} \text{ eV}^2$ and different values of $\sin^2 2\theta_{23}$ and $|U_{e3}| \equiv s_{13}$. Dotted line - no $s_{13}$ effect, and completely screened effect of 1-2 mixing; solid line - effect of 1-2 mixing only ($s_{13} = 0$); dashed line - the effects of interference for maximal 2-3 mixing (direct 1-2 contribution is screened); the dash-dotted line - the effect of interference and 1-2 mixing. For presently favored value of $\Delta m_{21}^2$ all the effects which involve 1-2 mixing should be enhanced by factor 1.5. Also shown are the SuperKamiokande experimental points.

The interference term gives the dominant contribution to the excess of $e$-like events if 2-3 mixing is close to the maximal one. In maximum we find:

$$\epsilon^{\text{int}} \sim 0.16 s_{13}. \quad (13)$$

### 3.5. Sterile neutrinos

The $\nu_{\mu} - \nu_s$ oscillations are excluded as the dominant solution of the atmospheric neutrino problem. The data give also strong bound on partial transition to the sterile component, $\nu_{\mu} \to \cos \theta_s \nu_s + \sin \theta_s \nu_s$: $\sin^2 \theta_s < 0.2 - 0.3$
in the context of single $\Delta m^2$.

Existence of sterile neutrinos can lead to new manifestations in the context of more than one $\Delta m^2$. The fourth neutrino with $\Delta m^2 \sim (0.5 - 1) \text{ eV}^2$ (motivated by LSND) has the MSW resonances in matter of the Earth in the energy range $(0.5 - 1.5) \text{ TeV}^{26}$. For the $(3+1)$ scheme with normal mass hierarchy the resonances, and consequently, the resonance enhancement of oscillations, are in the $(\nu_e - \nu_s)$ and $(\bar{\nu}_\mu, \bar{\nu}_\tau - \bar{\nu}_s)$ channels. The oscillations driven by $\Delta m^2_{LSND}$ lead to $^{26}$

![Image](image.png)

Figure 4. The zenith angle distributions of the upward-going muons for different mass and mixing scenarios with large $\Delta m^2$. From $^{26}$.

1). modification of the the zenith angle distribution of the upward-going muons (disappearance due to transition into sterile state),

2). appearance of fluxes of the electron neutrinos (strongly suppressed in the original flux at high energies) and tau neutrinos. These fluxes produce via the CC interactions an additional contribution to the cascade events.
For neutrinos crossing the core of the Earth the parametric enhancement of oscillations take place. The zenith angle distributions of events calculated for the Ice-Cube detector are shown in the fig. 4.

4. LSND: ultimate neutrino anomaly?

Three different possibilities to reconcile the LSND signal with the solar and atmospheric neutrino results are under discussion: (i). Additional sterile neutrinos in the context of (3+1) or (3+2) schemes; (ii). Non-standard neutrino interactions; (iii). CPT violation.

KamLAND and some other recent results have changed status of these possibilities.

4.1. (3 + 1) scheme

The main problem of the (3 + 1) scheme (fig. 5) is that the predicted LSND signal, which is consistent with the results of other short base-line experiments (BUGEY, CHOOZ, CDHS, CCFR, KARMEN) as well as the atmospheric neutrino data, is too small: the probability is about 3σ below the LSND measurement. Introduction of the second sterile neutrino with \( \Delta m^2 > 8 \text{ eV}^2 \) may help. It was shown that the second neutrino with \( \Delta m^2 \sim 22 \text{ eV}^2 \) and specific mixing parameters can enhance the predicted LSND signal by (60 - 70) % in comparison with (3 + 1) scheme.

However, the additional sterile neutrino aggravates the cosmological problems. This second (as well as the first one) sterile neutrino equilibrates in the Early Universe unless significant (\( > 10^{-5} \)) lepton asymmetry existed in the epoch with \( T \sim 10 - 20 \text{ MeV} \) and later. Equilibrium concentrations violate the nucleosynthesis, large scale structure bounds.

Mild (factor of 2 - 3) improvement of the present CDHS bound on \( \nu_\mu \) disappearance (by MiniBOONE) can exclude these possibilities. Also improvements of the BUGEY \( \bar{\nu}_e \) - disappearance bound (probably by the new generation of the reactor experiments) can do similar job.

Notice that the (3 + 1) scheme is of interest even independently of the LSND result. The mass gap of the fourth (mainly sterile) neutrino with active states can be arbitrary. The existence of such a neutrino can be motivated by the large lepton mixing. Even very small coupling of sterile neutrino can modify the original 3 \times 3 mass matrix with small flavor mixing in such a way that the flavor mixing will be enhanced.

On the other hand, possible existence of mixing with sterile neutrino leads to uncertainty in interpretation of the results on neutrino masses.
and mixing unless the additional neutrinos will be discovered and their characteristics measured.

4.2. Non-standard neutrino interactions

The LSND signal could be due to the anomalous decay of muon $^{31}$:

$$\mu^+ \to \bar{\nu}_e \bar{e} e^+, \quad (i = \epsilon, \mu, \tau). \quad (14)$$

Violation of the lepton number by two units, $|\Delta L| = 2$, allows to avoid stringent bound from non-observation of the $\mu \to eee$ mode. The decay (14) can be induced by the exchange of new neutral scalar boson ($M \sim 300 - 500$ GeV). As a result, the Lorentz structure of the decay differs from the standard one: the Michel parameter equals $\rho = 0$.

The problem of this interpretation is to reconcile “LSND with KARMEN”. Now one cannot play with difference of the baselines and the situation is equivalent to the averaged oscillation case (large $\Delta m^2$) where KARMEN gives stronger bound, essentially excluding the LSND result. The $\rho = 0$ feature of new interaction does not help $^{32}$.

New experiment TWIST at TRIUMPF $^{33}$ will measure the Michel parameter with high accuracy which will allow us to check deviation from the standard value $\rho = 3/4$.

4.3. CPT-violation

After KamLAND the ultimate possibility is the spectrum with $\Delta m^2_{\text{sun}}$ and $\Delta m^2_{\text{atm}}$ splittings in the neutrino channel and $\Delta m^2_{\text{LSND}}$ and $\Delta m^2_{\text{KL}}$ splittings in the antineutrino channel $^{34,35}$. 

Figure 5. The mass and flavor spectrum of the $$(3+1)$$-scheme.
In this case, no oscillation effect should be seen by LSND in the neutrino channel (decay in flight sample). In fact, here the evidence of oscillations is at level 1σ only.

The main problem of the model is the description of the atmospheric neutrino data (tension between the zenith angle distribution of the $\mu$-like events and the excess of the $e$-like events). In the antineutrino channel, the oscillations driven by $\Delta m^2_{LSND}$ are averaged and the effect due to $\Delta m^2_{KL}$ is relatively weak. Furthermore, according to $^{35}$, the best fit corresponds to the non-maximal $\bar{\nu}_\mu - \bar{\nu}_\tau$ mixing. In this case the screening factor (9) is not small and one expects significant effect of the $\bar{\nu}_e$ oscillations driven by the KamLAND oscillation parameters. A rough estimation gives ($\sim 10-15\%$) excess of the $e$-like events in the sub-GeV range.

According this scheme, KamLAND does not check solar neutrino solution and therefore whole spectrum of possibilities (LOW, VO, SFP) is not yet excluded. For MiniBOONE one predicts null oscillation result in the neutrino channel, but positive signal in the antineutrino channel.

5. Supernova Neutrinos

The KamLAND result has important impact both on the interpretation of the signal from SN1987A and on the program of future SN neutrino detection.

“After KamLAND” we can definitely say that the effects of antineutrino flavor conversion have been observed already in 1987: namely, effects of

- $\bar{\nu}_e$ conversion inside the star,
- (probably) oscillations in the matter of the Earth; furthermore the oscillation effects were different for Kamioka, IMB and Baksan detectors.

Specific effects depend on the type of mass hierarchy and value of $s_{13}$. In the case of normal mass hierarchy the adiabatic $\bar{\nu}_e \rightarrow \bar{\nu}_1$ and $\bar{\nu}_{\mu,\tau} \rightarrow \bar{\nu}_2$ transitions occurred inside the star and then $\nu_1$ and $\nu_2$ oscillated inside the Earth.$^{36}$

With future SN burst detections one can

(i) get information about $s_{13}$ (put upper or lower bound or measure it, depending on the true value of $s_{13}$),
(ii) establish the mass hierarchy,
(iii) test existence of sterile neutrinos.

Main problem of this program is that the original fluxes are not well known. Moreover, the neutrinos of all species are produced in the cooling phase which substantially diminishes the observable effects. (The effects
are proportional to the difference of original fluxes.)

Identification and comparison of the neutrino and antineutrino signals is crucial. However, small number of the expected $\nu_e$ events adds more uncertainties. So, developments of the high statistics $\nu_e$-detectors of SN neutrinos are highly welcomed.

In this connection, an important task is to find the “star model-independent” observables which encode the information about conversion effects.

5.1. LBL with supernova neutrinos

Study of the Earth matter effects on the SN neutrinos is one possibility to get “star model-independent” information on neutrino parameters. In a sense one can perform the long baseline experiment with SN neutrinos. The beam uncertainties are controlled if (i) two well separated detectors are used, (ii) properties of medium are known. Comparison of signals from the two detectors allows one to establish effect of oscillations inside the Earth.

If $\sin^2 \theta_{13} > 10^{-4}$, the appearance of the Earth matter effect in $\bar{\nu}_e$ ($\nu_e$) channel will testify for the normal (inverted) mass hierarchy. Independently of $\sin^2 \theta_{13}$ value, the very fact of the absence of the Earth matter effect in the $\nu_e$ ($\bar{\nu}_e$) channel will exclude the inverted (normal) mass hierarchy.

Actually, the existence of the Earth matter effect can be established with one detector: at high energies one predicts characteristic oscillatory distortion of the energy spectrum which increases with energy.

5.2. Shock wave effect

It was argued recently that the shock wave may reach the region of the neutrino conversion, $\rho \sim 10^4$ g/cc, after $t_s = (3 - 5)$ s from the bounce (beginning of the burst). Changing the density profile and therefore the adiabaticity, the shock front influences the conversion in the resonant characterized by the atmospheric $\Delta m^2_{13}$ and $\sin^2 \theta_{13}$, provided that $\sin^2 \theta_{13} > 10^{-6}$.

The following shock wave effects should be seen at some level in the neutrino (antineutrino) for normal (inverted) hierarchy:

1). Change of the total number of events in time;
2). Wave of softening of the spectrum which propagates in the energy scale from low energies to high energies;
3). Delayed Earth matter effect in the “wrong” channel (e.g., in neutrino channel for normal mass hierarchy).
Modification of the density profile by the shock wave leads to appearance of additional resonances below the front. Effects of these resonance have been considered recently in \(^{42}\).

Monitoring the shock wave with neutrinos is challenging but really exciting task which certainly deserves further considerations. Studying the shock wave effects on the properties of neutrino signals one can (in principle) get information on (i) time of shock wave propagation, (ii) shock wave revival time, (iii) velocity of propagation, (iv) density gradient in the front, (v) size of the front. This, in turn, can shed some light on the mechanism of star explosions.

6. Standard and Non-standard

What is standard in the neutrino physics now:

- three neutrinos;
- masses below 0.5 – 1 eV;
- bi-large or large-maximal mixing;
- non-zero 1-3 mixing, probably close to the present upper bound;
- smallness of neutrino mass related to the neutrality of neutrinos and their Majorana nature.

What is beyond the standard picture? (i) new neutrino states (sterile neutrinos), (ii) new neutrino interactions; (iii) large anomalous magnetic moments, etc.. What is exotic? Effects of violation of the Lorentz invariance, CPT violation, equivalence principle, etc..

With the KamLAND result and resolution of the solar neutrino problem we made the next (after establishing the oscillations in atmospheric neutrinos) major step in reconstruction of the neutrino mass and mixing spectrum:

1). the mass squared split of \(\nu_1\) and \(\nu_2\) states, \(\Delta m^2_{12}\), is determined;

2). distribution of the electron flavor in \(\nu_1\) and \(\nu_2\) states is measured (the best fit corresponds to \(|U_{e1}|^2 \approx 2|U_{e2}|^2|\);

3) distribution of the muon and tau flavors in \(\nu_1\) and \(\nu_2\) can be found with precision \(O(s_{13})\) from the unitarity condition.

These results are summarized in fig. 6 which shows also what should be determined to accomplish the picture:

- \(U_{e3}\);
What we cannot see in the plot is the CP-violating phases: Dirac phase $\delta$, and if neutrinos are Majorana particles, two Majorana phases. One needs also to establish the nature of neutrinos (Majorana-Dirac), or in general to measure their “Majorana character”. For a system of neutrinos one can introduce a parameter, related to the lepton number whose change transforms pure Majorana neutrinos to quasi-Dirac and then to the Dirac neutrinos.

In this connection, the $\beta\beta_{0\nu}$ decay experiments are of the highest priority: the results will contribute (together with other measurements) to determination of all unknown elements listed above.

The KamLAND result and selection of the LMA solution has crucial consequences for the $\beta\beta_{0\nu}$ decay searches and interpretation of their results. Now we can say that due to the large 1-2 mixing, there is a strong dependence of the effective Majorana mass of the electron neutrino, $m_{ee}$, on the CP-violating phases. This in turn, implies a possibility of substantial cancellation of contributions to $m_{ee}$ from different mass eigenstates. Consequently, it is not possible to determine the absolute scale of neutrino mass from the $\beta\beta_{0\nu}$ decay immediately.
7. Conclusions

In this paper I have discussed topics on which the KamLAND result has an immediate impact. Furthermore, only aspects related to the phenomenology of the neutrino mass and mixing have been covered. Even with these restrictions the review is far from being complete. I should mention here physics of the long baseline experiments elaborated largely before KamLAND. The first KamLAND result with confirmation of LMA has given further boost for realization of its experimental programs.

The main developments in neutrino physics during last 30-35 years were related to various neutrino anomalies both real and fake. The review covered status of the anomalies after KamLAND with the questions: “What is left” and “what are perspectives”?

One can imagine several scenarios:

- “Standard scenario” described in sect. 6: there is a well defined program of reconstruction of the neutrino mass and flavor spectrum. It is characterized in terms of further tests, precision measurements, searches for new physics.
- Confirmation of the LSND result will open new perspectives related to existence of new light neutral fermions, or CPT violation, or new interactions.
- New anomalies may appear which will lead to something unexpected (some hints from NuTeV, Z^0-width measurements?).

“Without anomalies”: we will work on the well defined program which consists of

1). Determination of masses, mixings, CP-phases; precision measurements of parameters. Here, we face “technological problems”: determinations of the absolute mass scale and CP-phases are indeed big challenge.

2). Searches for new physics beyond the standard picture, restrictions on exotics. The main issues are new neutrino interactions, new neutrino states, effects of violation of CPT, Lorentz invariance, equivalence principle, Pauli principle.

3). Identification of origins of the neutrino mass and mixing: that can include reconstruction of neutrino mass matrix, tests of the see-saw mechanism and other possibilities (flavor violation processes, leptogenesis, high energy experiments).

4). Applications of our knowledge of neutrino mass and mixing to Geophysics, Astrophysics, Cosmology.
Notice that future high energy experiments (LHC, TESLA ...) may have serious impact on this program.

For details and further developments, see the talks at NOON2003.

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