Review on neutrino properties.

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Abstract. A short summary of the situation on neutrino properties at the time of the workshop is presented. It is intended for non neutrino specialists, as are many participants to this workshop. Ongoing experiments and projects are underlined.

1. Introduction
I have been asked to review $\nu$ physics for this workshop. Since double $\beta$ was discussed in a dedicated session, it will be only briefly mentioned here. The outline of this paper is as follow: a short review of the importance of $\nu$ in the universe is presented. After a reminder of the theoretical framework, a review of the present situation of direct mass measurements and oscillations is presented. Then I discuss ongoing and future experiments, after specifying what are their goals.

2. $\nu$ and the universe.
From our knowledge of cosmology, what can be said about $\nu$?

- We expect relic neutrinos from Big Bang. We guess a fraction of a % of the content of the universe. Neutrinos play a role in BBN and the formation of large scale structures, they delay their formation because of their smearing power. Comparaison of cosmological models with observation tells that the sum of masses is $\leq \sim 1\ eV$.
- They could contribute to the dark energy, if they would possess a new force (variable mass neutrinos [1]).
- we expect diffuse neutrinos from supernovae.
- neutrinos from atmosphere, sun and SN1987A have been observed, some high energy ones are expected from energetic sources.
- neutrinos can provide the clue to baryon-antibaryon asymmetry of the universe (leptogenesis).

3. neutrinos and theory
In our standard electroweak theory, there are things which can be said and other ones not said about neutrino properties :

- Left-handed neutrinos are in doublets with charged leptons.
- Right-handed leptons are in singlets.
- there are 3 families.
• initial simplicity assumption about common null mass is wrong.
• Are $\nu$ their own antiparticle? Are they Dirac or Majorana or both?
• what are their masses?
• sterile $\nu$ is beyond SM.

In EW theory, flavor $\nu_\alpha$ are linear superpositions of massive $\nu_i$ (see fig. 1) where $U_{PMNS}$ is a unitary matrix strictly analog to CKM matrix. One can write this matrix as a product of 3 rotations, one of them containing one CP violating phase $\delta$ (Dirac case). If $\nu$ were of Majorana nature, the arbitrary choice of phases would be restricted with respect to the Dirac case, and there would be 2 additional CP phases included in the diagonal $V^CP_M$ matrix, which otherwise is identity.

This description of flavor states offers the possibility of transitions of one flavor $a$ to another $b$ according to:

$$P(\nu_a \rightarrow \nu_b; L) = |\Sigma_i U_{bi} e^{-\frac{i m^2_{a}}{2E} L_{a}} |^2$$

where $m_i$ are the masses, $L$ the distance travelled by the $\nu$ and $p$ its momentum.

Actually, most experiments can be described to a good approximation by a 2-flavor oscillation formula, the matrix becomes:

$$|\nu_a >= +\cos \theta \ |\nu_1 > +\sin \theta \ |\nu_2 >$$
$$|\nu_b >= -\sin \theta \ |\nu_1 > +\cos \theta \ |\nu_2 >$$

and the transition probability:

$$P = \sin^2(2\theta)\sin^2(1.27(L_{[km]}/E[GeV])\Delta m_{[GeV^2/c^4]}^2)$$
For $\nu$ born in the sun, this is not valid, because of the strong matter effect described by MSW theory.

4. Direct mass measurements

Direct mass measurement has been achieved by means of the energy measurements of $\beta$ decay spectra.

For more than 25 years, the field has been dominated by spectrometers, magnetic and then electrostatic. Since they look only at the end point of the spectrum, they can use intense source of medium lifetime $\beta$ emitter, tritium($E_0 = 18.6\text{keV}, T_{1/2} = 12.2\text{y}$). They have good energy resolution, around 1 eV. But uncertainties due to the excited states, scattering and absorption in the source imply good understanding. The best results obtained so far are[2]:

for Mainz :

$$m_{\nu}^2 = -0.6 \pm 2.2\text{stat.} \pm 2.1\text{syst.}$$
$$m_\nu \leq 2.3\text{eV (95\%CL)}$$

and for Troitsk :

$$m_{\nu}^2 = -1.2 \pm 2.2\text{stat.} \pm 2.1\text{syst.}$$
$$m_\nu \leq 2.2\text{eV (95\%CL)}$$

More recently, bolometers (experiments MANU and MIBETA) entered into the field, with the advantage of detecting all released energy, including the excited states. The difficulties are linked to the slowness of the thermal signal : one need many small detectors to avoid pile-up. The chosen emitter is $^{187}\text{Re}$ which decays to $^{187}\text{Os}$ with a low $Q$ value($E_0 = 2.46\text{keV}$). They are reaching a sensitivity of about 2 $\text{eV}$.

5. Oscillations.

Most of the results about $\nu$ mass - and the only ones so far with positive results -, come from oscillation.

Initial indication from Homestake, starting in 1967, showed the solar $\nu$ puzzle. Thanks to KamiokaNDE, GALLEX, SAGE, GNO, SuperKamioka and SNO, the solution of the puzzle is now widely accepted : $\nu_e$ produced inside the sun change flavor through the sun matter by MSW effect. The beautiful SNO NC and CC detector confirms the initial calculation of of $\nu_e$ flux production inside the sun, and the KAMLAND reactor experiment sees the corresponding vacuum oscillation. It is described by $\theta_{12}$ and $\Delta m_{12}^2$ (angle and difference of squared masses).

Starting at the end of the eighties, the 1kt Cherenkov KamiokaNDE detector observed an anomaly on the ratio of $\nu_\mu$ to $\nu_e$ produced by cosmic rays in the atmosphere : the relative ratio $\nu_\mu/\nu_e$ was significantly smaller than the predicted value, which is close to the naive value of 2 and not very model-dependent. In 1998, the 50 kt Cherenkov SuperKamioka detector studied this anomaly as a function of the zenithal direction of the detected $\nu$. It confirmed the anomaly and established the oscillation as a reasonable explanation. Further data point to an oscillation towards a flavor $\neq$ electron. This oscillation is described by $\theta_{23}$ and $\Delta m_{23}^2$.

At about the same time, the CHOOZ reactor experiment did not observe any disappearance of $\bar{\nu}_e$, for $L/E$ values in the range suggested by SuperKamioka. More recently, the accelerator Long baseline experiments K2K and MINOS have confirmed the SuperKamioka observation.

These results on $\nu$ oscillations fit well within the standard electroweak theory with 3 flavors of light $\nu$'s.

Fig. 2 from [3] summarizes the parameters values which describe these 2 oscillations, they have been obtained by a global fit of all available data mentioned above.
However, in the nineties, the LSND experiment at Los Alamos found evidence for $\nu_e$ appearance in a $\nu_\mu$ beam, with $\Delta m^2$ of the order of 1 eV$^2$. This is inconsistent with the requirement of a world with 3 families: the algebraic sum of the mass squared difference must be zero, and the LSND range does not fit with the 2 other values from solar and atmospheric oscillation. Conventional theoretical explanation of the LSND results is based on the existence of one (or more) sterile $\nu$.

6. The present goals.

At this stage of experimental observations what should we do, what should we measure?

- It is mandatory to confirm or infirm LSND results: sterile $\nu$ would be a revolution in particle physics, and presumably beyond.
- The cross mixing matrix need more investigation:
  - Can we observe a non-zero value of $\theta_{13}$, namely a $\nu_{\mu,\tau}\leftrightarrow\nu_e$ transition at the atmospheric $L/E$?
  - If yes, can we measure the $CPV (\sin \delta \neq 0)$?
- We need to measure the mass hierarchy, namely the sign of $\Delta m^2_{23}$ ($m_3 > m_1$ or $m_3 < m_1$). (see fig.3)
- We need to confirm the $\nu_{\mu, \tau} \leftrightarrow \nu_e$ transition at the atmospheric regime.
- We need to precisely measure all parameters of the mixing matrix in order to validate the standard $\nu$ oscillation scenario.
- We want to pursue the investigation of the Majorana VS Dirac property of $\nu$, down to $\sqrt{\Delta m^2_{23}} \approx 0.05$ eV which is the lower limit if nature has chosen the inverted hierarchy.
7. Ongoing and future experiments.

7.1. Determination of the $\nu$ mass scale.

So far, we have 3 means of accessing the $\nu$ mass scale:

- Direct mass measurements.
  - Spectrometers: The Mainz and Troitsk collaborations have joined and are working on the KATRIN project. This could reach a sensitivity of 0.2 eV around 2015.
  - Bolometers: the MANU and MIBETA collaborations have joined and are working on the MARE project. This could reach a sensitivity of 0.2 eV around 2015.

- $0\nu\beta\beta$ decay.
  The main aim is to reach or approach $\sqrt{\Delta m^2_{23}} \cong 0.05$ eV. Several techniques will be used\cite{4}: bolometers(CUORE), tracker and calorimeter(SuperNEMO), crystals and/or liquid argon(GERDA,MAJORANA). Detectors of 1 t are envisioned.

- Cosmology: present studies will improve their precision, and more observation means will be used, e.g. gravitational lensing. The sensitivity to $\Sigma m_i$ could go down to 0.05 eV\cite{5}.

7.2. Oscillations.

The SNO detector has just stopped data taking, more results are expected, more particularly with the 3rd phase, where $^3H_e$ counters have been used for the capture of neutrons and should provide excellent signal to noise.

The SuperKamioka detector has resumed data taking with nominal photocathode coverage($\sim 40 \%$) and is improving electronics. It will continue to study solar and atmospheric $\nu$'s, and look for SuperNovae explosions and diffuse flux. For these last topics, it maybe loaded with $G_d$ in order to improve the detection of neutron capture. Starting in 2009, it will be the
far detector of the T2K long baseline experiment: a new accelerator complex and beam line under construction at Tokai, 295 km away, is expected to produce intense beam of $\nu_\mu$'s, with a beam power approaching 1 MW. The main goal of T2K is to reach a sensitivity of 0.01 for $\sin^2(2\theta_{13})$ (at $\sin\delta = 0$). It applies the "off axis" concept, which allows to have more $\nu_\mu$ flux at the oscillation peak (700 MeV), and less $\nu_e$ contamination in the beam.

Along the same line, the NO$\nu$A experiment, not yet funded, is designed to be off-axis of the (potentially upgraded) MINOS NUMI beam, at a distance larger than 800 kms from the source: at that length, and since it operates at larger energy (2 GeV), it will be sensitive to matter effect and may determine the hierarchy of $\nu$ masses. It is a very long and massive (25 kton fiducial) liquid scintillator located on the ground.

The 1kt KAMLAND experiment, in Japan, located at an average of 170 km from reactor will continue reactor physics. A liquid scintillator purifying station is being implemented and will allow to measure solar neutrinos (and to do geophysics with $\nu$'s from earth).

In the same category, the 300 t BOREXINO(Gran Sasso, Italy), after a long delay consecutive to some pseudocumene leak, should start soon.

MINOS(fig. 4) is a long baseline experiment in the US: $\nu$'s produced at FNAL travel 730 km to reach the detectors in the Soudan mine. It consists of magnetized coarse grain calorimeter. The total mass is 5.4 kt. It has already produced competitive results on disappearance[7](fig. 7), and has some sensitivity on $\nu_e$ appearance. It is expected to run for several years. It also has some sensitivity to $\nu_e$ appearance.

The OPERA experiment in Gran Sasso is also a long baseline with a similar distance to MINOS, but with a higher energy beam spectrum: the goal is to detect the appearance of $\nu_\tau$. The commissioning of the beam has started this year, and will continue in 2007 after fixing some leak problem on the magnetic focussing horn/reflector. The experiment itself(fig. 5) consists of 2 sets of a 1kt tracker/target followed by a muon spectrometer. The target mass is provided by
Figure 5. Sketch of the OPERA experiment and of the strategy for finding $\tau$ candidates in the bricks([6]).

lead sheets interleaved with emulsions for tracking. The basic unit is the brick. Bricks are to be removed when outside electronic device has signaled a $\nu$ event inside. The bricks are starting to be installed, whereas the spectrometers and some brick have already been operated and seen muons induced by the $\nu$ beam (fig. 6). OPERA expects a background of $\sim$ 1 event, with a signal between 10 and 20 during the 5 year planned operation.

The MINIBOONE experiment (fig. 8) has been designed to solve the LSND mystery. They have accumulated data in $\nu$ and have been recently running with $\bar{\nu}$. They are doing a blind analysis of their data: fig. 9 shows the energy spectrum of candidate $\nu_e$ events. Only events whose energy is larger than 2 GeV are shown, whereas the contributions from simulation are displayed for the entire spectrum.

Several projects of reactor experiments plan to improve the CHOOZ upper limit on $\theta_{13}$ by at least one order of magnitude. They improve the CHOOZ concept with 2 main driving ideas:

- They will use 2 or more identical liquid scintillator detectors in order to suppress the systematic uncertainties coming from unperfect knowledge of reactor power and spectra. Relative systematics on counts will be better than a $\%$, and there will be good or excellent relative energy calibration.
- Each detector will be made of 3 volumes: inside is a the $\bar{\nu}_e$ target of Gd-loaded liquid scintillator, then comes another liquid scintillator, the $\gamma$-catcher, followed by a transparent buffer dedicated to absorption of outside background. The first to operate should be the double-CHOOZ(2 reactors, 2 detectors), and there exist more ambitious projects, with multi reactors and multidetectors.
Figure 6. Display of some first OPERA beam events ([6]).

Figure 7. Oscillation Contour of the 2006 MINOS result compared to previous results from SuperKamioka (standard analysis and high precision L/E) and K2K ([7]).
Figure 8. A sketch of the MINIBOONE beam and experimental setup.

Figure 9. Preliminary results from MINIBOONE for large $E_\nu$ energy and simulated contributions at all energies.
8. The longer term
The previous section dealt with experiments which are expected to provide results within 10 years.
On the longer term - at least for the oscillations - people imagine future beam and detector facilities. The main aim is to access a large part of the possible CP violation in the neutrino sector, CP violation which is favored in the leptogenesis scenario about the baryon-antibaryon asymmetry of the universe. Let us mention a few of them:

- Various ideas of powerful superbeams coupled to supermassive detectors are under study: MEMPHYS, a CERN based beam coupled to a megaton Cherenkov under the Frejus mountain (France/Italy). HYPERK, a major extension of T2K with similar megaton detector and more beam power. UNO, a US counterpart of these ideas. There exist also arguments for intense on-axis wide-band beams (BNL).
- For the last 10 years or so, the concept of neutrino factory has gained momentum. It requires to produce and cool intense muon beams. An experiment in UK, MICE, will do some R&D on cooling soon. The detector(s) would be a massive iron tracker/calorimeter, magnetized in order to measure the muon sign.
- Following the idea of P. Zuchelli, radioactive β beams are also under study. For some values of $\theta_{13}$ it may compete with a neutrino factory. Various pairs of energy-distance are considered.

9. Conclusion.
The field of experiments studying neutrino properties is very active. Non zero $\nu$ masses are well established from atmospheric and solar $\nu$ data and confirmed by experiments with artificial $\nu$
sources. Astrophysics and cosmology enter into the game at the $eV$ level. The issue of sterile(s) neutrino is opened and maybe clarified soon. New experiments on $0\nu\beta\beta$ decay, oscillations or direct mass measurement have started recently and some will start soon. Detailed ideas and experimental R&D are worked out for experiments which will start in 10 or 20 years from now. To summarize about oscillations the scenario(fig. 10,[8]) of experimental time evolution of the sensitivity to $\theta_{13}$ in the next decade gives a feeling of the trend in the field.

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References
[1] R. Fardon, A. E. Nelson and N. Weiner, JCAP 0410, 005 (2004) [arXiv:astro-ph/0309800].
[2] P.Doe, "Direct neutrino mass measurements", presentation at $\nu'$2006, Santa Fe.
[3] F.Feruglio, "Neutrino Masses, Mixing", presentation at ICHEP'06, Moscow.
[4] A. Bettini "Astro-Particle Physics", presentation at ICHEP 2006
[5] S. Dodelson, "Precision Cosmology and neutrinos", presentation at Neutrino'2006, Santa Fe.
[6] M. Cozzi, "The OPERA experiment", Presentation at IPRD'06, Siena 2006.
[7] D. G. Michael et al. [MINOS Collaboration], Phys. Rev. Lett. 97, 191801 (2006) [arXiv:hep-ex/0607088].
[8] A. Blondel, A. Cervera-Villanueva, A. Donini, P. Huber, M. Mezzetto and P. Strolin, Acta Phys. Polon. B 37, 2077 (2006) [arXiv:hep-ph/0606111].
[9] R.Rameika, "New Results from Accelerator Neutrino Experiments", presentation at ICHEP'06, Moscow.