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Working group report: Neutrino physics

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Abstract. This is the report of the neutrino physics working group at WHEPP-X. We summarize the problems selected and discussed at the workshop and the papers which have resulted subsequently.

Keywords. Neutrino oscillations; neutrino mass models; leptogenesis; lepton flavour violation.

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1. Introduction

It was decided to cover a myriad of topics for discussion and work in the neutrino physics working group, rather than restrict ourselves to any one focal theme.

There were two plenary talks. The first one was on *Neutrino oscillations: Present status and outlook* by Thomas Schwetz, who updated us on the current situation in neutrino oscillation physics. The second plenary talk was on *Future neutrino experiments* by Takaaki Kajita, who presented a global review of the upcoming neutrino experiments and their expected sensitivity reach for neutrino oscillation parameters.

A substantial amount of discussion, including two working group talks, revolved around constraining neutrino mass models, both from data and symmetry considerations. The non-overlapping talk on *The see-saw mechanism: Neutrino mixing, leptogenesis and lepton flavour violation* by Werner Rodejohann covered the current status of neutrino models under the see-saw framework and related phenomenology. The overview talk *Flavor symmetries and neutrino mass models* by Martin Hirsch, on the different versions of the mass models based on A_4 symmetry in the flavour sector, was attended by both the neutrino physics and beyond the Standard Model working groups.

Other working group talks were the state-of-art reviews on: *Atmospheric neutrinos: Aspects and prospects* by Pomita Ghoshal, *Potential of long baseline experiments* by Sanjib Agarwalla and *Collective flavour oscillations of supernova neutrinos* by Basudeb Dasgupta. In addition, there were informal presentations during the workshop. In particular, Manoj Kaplinghat presented an extensive overview of the current bounds on the sum of neutrino masses from cosmological data.

The three missing links in our current understanding of neutrino mixing are (i) the mixing angle θ_{13}, (ii) the $\mathrm{sgn}(\Delta m^2_{31})$, *a.k.a.*, the neutrino mass ordering and (iii) the CP phase δ_{CP}. All these three neutrino parameters give rise to tiny effects and are therefore hard to detect. Future experiments would be mainly addressing these three issues. Pomita Ghoshal reviewed the comparative sensitivity reach of atmospheric neutrino experiments with a large magnetized iron detector (INO), *vis-á-vis* that with a megaton water Čerenkov detector. Sanjib Agarwalla discussed the need to go beyond the next range of neutrino experiments by building very powerful neutrino beams such as beta-beams and neutrino factories.

Neutrino oscillation physics also has an impact on neutrino spectra from supernovae. There is considerable new understanding of non-linear effects in supernova dynamical evolution due to flavour mixing. Basudeb Dasgupta's talk covered recent developments in supernova neutrino physics.

On the first day the group met and decided on six broad discussion topics, each to be led by a 'discussion leader'. Following are the list of topics identified, along with the name of the discussion leader:

1. Viable model for the 3+2 mass spectrum – *Werner Rodejohann*
2. Dirac see-saw and leptogenesis – *Sandhya Choubey*
3. Neutrino telescopes and parameter degeneracies – *Srubabati Goswami*
4. Collective effects in supernova neutrinos – *Amol Dighe and Basudeb Dasgupta*
5. Tau production and detection for neutrinos – *D Indumathi*
6. GLoBES tutorials – *Thomas Schwetz*

We now discuss these issues in greater detail.

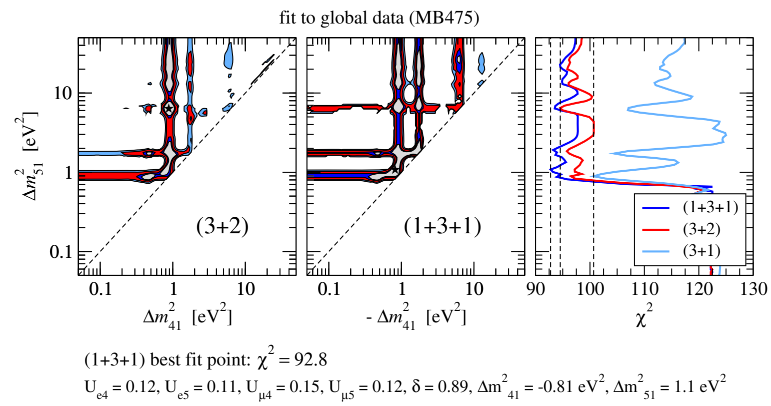

Figure 1. Allowed areas in the 3+2 parameter space (generated by Thomas Schwetz at WHEPP-X).

1.1 *Viable model for the 3+2 mass spectrum*

S Agarwalla, A Bandyopadhyay, S Choubey, S Goswami, M K Parida, G Rajasekaran, S Ray, W Rodejohann and T Schwetz

Two extra sterile neutrinos are needed to reconcile the LSND signal with the rest of the world neutrino data. The so-called 3+2 neutrino mass scheme results in eight possible mass spectra [1], which are perfectly consistent with current neutrino oscillation data. W Rodejohann briefly discussed these mass spectra and the constraints on them from cosmology, neutrinoless double beta decay and beta decay. This scheme consists of five neutrino masses, ten mixing angles and 15 CP violating phases. Thomas Schwetz provided the bounds on these parameters from the neutrino oscillation data. A re-analysis at WHEPP for the mass spectra not considered in his earlier paper [2] gave results shown in figure 1. Since the sterile mixing angles are small, it is expected that

$$\mathcal{M}_{\rm F} = \begin{pmatrix} & 3\times 3 & & \epsilon & \epsilon \\ & \text{active} & & \epsilon & \epsilon \\ & \text{block} & & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon & a & \epsilon \\ \epsilon & \epsilon & \epsilon & \epsilon & b \end{pmatrix} \qquad (1)$$

with $a \simeq m_4$ and $b \simeq m_5$. $\mathcal{M}_{\rm F}$ can be calculated for all the eight possible spectra. Shamayita Ray calulated the mass spectra using $\theta_{13} \simeq \theta_{23} - 45^\circ \simeq \mathcal{O}(\epsilon)$ and all sterile mixings $\mathcal{O}(\epsilon)$. Effort is on to find a viable model for the mass matrix obtained.

1.2 *Dirac see-saw and leptogenesis*

S Agarwalla, S Choubey, E J Chun, A K Giri, S Goswami, M Hirsch, R Mohanta, M K Parida, P Roy and W Rodejohann

The generation of a lepton asymmetry at a high scale is a crucial first step in the mechanism of baryogenesis via leptogenesis and is usually achieved through CP-violating decays of a heavy Majorana neutrino. Another way, without such an intrinsic lepton number violation, is through baryogenesis via Dirac leptogenesis: Suppose the neutrinos are Dirac fermions which acquire small masses through suppressed Yukawa couplings. Decays of very heavy fields in the early universe would have produced equal numbers of such neutrinos and antineutrinos, distributed into left-handed and right-handed components. During the sphaleronic transition, the left-handed lepton number got converted to baryon number. But the right-handed neutrinos, being $SU(2) \times U(1)$ singlets with small Yukawa couplings, remained hidden from the sphalerons, thereby generating a net baryon asymmetry.

It was known that supersymmetry is needed to make such a model work. The sub-eV neutrino mass scale is generated by a combination of moderately small Yukawa couplings and very heavy $SU(2)$ doublet superfields with leptogenesis arising successfully from decays of the latter. However, the same heavy superfields also decay into right chiral sneutrinos, carrying masses of the order of several hundreds of GeV. These also would have small couplings related by supersymmetry to the Yukawas. Therefore, they would decay very slowly, surviving long after the decoupling temperature (∼10 GeV) of the LSP. They would behave like dark matter with a number density much in excess of the cosmologically allowed dark matter relic density. This has been the problem with supersymmetric Dirac leptogenesis.

At WHEPP, this problem was solved [3] in the context of the nearly minimal supersymmetric Standard Model (nMSSM). The nMSSM spectrum was extended only in the gauge singlet sector. The right chiral neutrino superfields N_i (i = 1,2,3 for the three generations), heavy pairs of chiral superfields Φ_k and Φ_k^C carrying B–L charges ±1 and a generic heavy singlet superfield X mediating supersymmetry breaking were included. By invoking dynamical supersymmetry breaking in the model of Dine, Nelson, Nir and Sherman, it was possible to generate large supersymmetry breaking parameters $\Lambda_\nu \sim 10^7$–10^8 GeV, without upsetting the sparticle mass spectrum, but considerably quickening the decays of the right chiral sneutrinos, so that the dark matter relic density becomes controllably small.

1.3 *Neutrino telescopes and parameter degeneracies*

S Agarwalla, A Bandyopadhyay, S Choubey, B Dasgupta, P Ghoshal, S Goswami, H S Mani, G Rajasekaran, S Ray, W Rodejohann and T Schwetz

Most long baseline experiments suffer from the so-called problem of parameter degeneracies, with multiple fake solutions in addition to the true one [4]. Resolving these degeneracies by combining ultra high energy neutrino data from neutrino telescopes with the long baseline data [5] was studied. Werner Rodejohann talked on detection of ultra high energy neutrinos and extraction of neutrino oscillation parameters using the flavour ratios at the neutrino telescopes. Ultra high energy neutrinos could come from pion, muon-damped or neutron sources and the flux ratio at source would be different for each of these sources. The observed flux at the detector $\phi_{\rm D} = \alpha^2\phi_\pi + \beta^2\phi_\mu + \gamma^2\phi_n$, where ϕ_π, ϕ_μ and ϕ_n are the fluxes from pion, muon-damped or neutron sources respectively, and α^2, β^2 and γ^2 are the

Table 1. Electron neutrino and antineutrino spectra emerging from a supernova. Here s_{12}^2 (c_{12}^2) stand for $\sin^2\theta_{12}$ ($\cos^2\theta_{12}$) and P_{13} is the effective jump probability between the neutrino mass eigenstates due to the MSW resonance.

Normal hierarchy	Inverted hierarchy
$F_{\nu_e} = s_{12}^2(P_{13}F_{\nu_e}^0 + (1-P_{13})F_{\nu_x}^0) + c_{12}^2 F_{\nu_x}^0$	$F_{\nu_e} = \begin{cases} s_{12}^2 F_{\nu_e}^0 + c_{12}^2 F_{\nu_x}^0 & (E < E_c) \\ F_{\nu_x}^0 & (E > E_c) \end{cases}$
$F_{\bar{\nu}_e} = c_{12}^2 F_{\bar{\nu}_e}^0 + s_{12}^2 F_{\bar{\nu}_x}^0$	$F_{\bar{\nu}_e} = s_{12}^2 F_{\bar{\nu}_x}^0 + c_{12}^2((1-P_{13})F_{\bar{\nu}_e}^0 + P_{13}F_{\bar{\nu}_x}^0)$

fraction of these sources in the universe. One can assume some 'true' value for the source composition and constrain the parameters α^2, β^2 and γ^2 through a χ^2 analysis. This work is in progress.

1.4 *Collective flavour oscillations of supernova neutrinos*

S Choubey, B Dasgupta, A Dighe, S Goswami, D Indumathi, M K Parida,
M K Parida and G Rajasekaran

Recently it has been recognized that close to the neutrinosphere, neutrino–neutrino interactions are significant, resulting in large flavour off-diagonal terms, and hence significant flavour conversion. Such a dense self-coupled gas of neutrinos and antineutrinos has nonlinear evolution. This ensures that the neutrinos exhibit synchronized oscillations, i.e. neutrinos of all energies oscillate coherently with an average frequency. These oscillations do not give rise to any effective flavour conversion since the effective mixing angle is highly supressed due to the large matter potential. As the neutrinos stream outward, the neutrino density becomes smaller, and bipolar oscillations begin to take place. In the case of inverted hierarchy, these oscillations have large amplitude even for a vanishingly small mixing angle. As the neutrinos transit from a region where collective effects dominate to a region where neutrino density is low, these bipolar oscillations can lead to a complete swapping of the $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra, where $x = \mu, \tau$. The ν_e and ν_x spectra cannot swap completely, because of lepton number conservation, and the swap occurs only above a certain energy, giving rise to a spectral split. Eventually, beyond a few hundred kilometers, the neutrino–neutrino interaction energy becomes negligible, and collective effects cease to be important. The fluxes of ν_e and $\bar{\nu}_e$ arriving at Earth are given in table 1. $F_{\nu_\alpha}^0$, etc., are the initial supernova neutrino fluxes while F_{ν_α} are the resultant fluxes emerging from the supernova.

Angular dependence of flavour evolution can give rise to additional features. However, even departures from spherical symmetry do not seem to modify the results in a qualitative way. Collective effects have also been investigated in the context of the neutronization-burst phase of O–Ne–Mg supernovae, which could allow a determination of the neutrino mass hierarchy even at vanishingly small θ_{13} [6].

At WHEPP the impact of collective effects on the diffuse supernova neutrino background (DSNB) flux was discussed. It was found that collective effects could change the fluxes by up to 50% from previous estimates. This work on DSNB fluxes has now been completed and is submitted for publication [7].

1.5 *Tau production and detection for neutrinos*

D Indumathi, T Kajita, H S Mani, M V N Murthy, S Uma Sankar and N Sinha

The detection of ν_τ through hadronic decays of the final state tau in Super-Kamiokande (SK) [8] was discussed by Takaaki Kajita. The possibility of detecting ν_τs in magnetized iron detectors, through the leptonic decay of the produced tau, was explored. This adds to the 'right' ('wrong') sign contribution to the μ (e) channel. Since wrong-sign events are the primary signals for precision measurements at neutrino factories, the tau contribution can severely compromise the sensitivity in the electron channel, while not significantly affecting the muon channel. This study is in progress [9].

1.6 *GLoBES tutorial*

S Agarwalla, A Bandyopadhyay, S Choubey, E J Chun, B Dasgupta, P Ghoshal, S Goswami, D Indumathi, S Ray, W Rodejohann and T Schwetz

Thomas Schwetz gave tutorials on installing and using the GLoBES software package [10]. GLoBES, which stands for general long baseline experiment simulator, is a versatile and powerful tool to study the physics potential of future long baseline experiments. It generates event rates at various proposed long baseline experiments and can be used to extract sensitivity reaches of these experiments to neutrino oscillation parameters. There were two tutorial sessions, which included a hands-on session where participants installed and ran the GLoBES software on their laptops.

2. Other activities

Other discussions included:

- Four zero neutrino Yukawa textures: For Type I see-saw and in the basis where the charged lepton and heavy right-handed neutrino mass matrices are real and diagonal, four has been shown to be the maximum number of zeros allowed in the neutrino Yukawa coupling matrix Y_ν [11]. Discussion on this topic resulted in a paper, which is now on the arXiv [12].
- MiniBOONE versus LSND: Various models have been put forth to explain MiniBOONE and LSND simultaneously, as well as to explain the upturn of the MiniBOONE spectrum at low energies. These papers were discussed in detail.
- Mass varying neutrinos: Issue of observing signatures of mass varying neutrinos in neutrino experiments was discussed.

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