Theoretical Neutrino Physics

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1. Introduction

Neutrino physics has in recent years gone through a phase of explosive development and matured into a dynamic research field where a number of breath-taking discoveries have been made. The discovery of neutrino masses and mixing is the first solid evidence for the long-sought "physics beyond the standard model". In addition, there exist intriguing connections to several other physical sciences such as geo-physics or helio-seismology. Neutrinos are here in a two-fold way unique probes of new physics. First, they allow one to obtain information on fundamental properties as, for example, the values of neutrino masses and mixings, the Majorana nature of neutrinos and leptonic CP violation. These properties require theoretical explanations which go beyond the standard model of particle physics and they lead to consequences in the greater context of elementary particle physics. Leptonic CP violation, for example, is likely connected to the baryon asymmetry of the universe. The second lever arm on new physics provided by neutrinos is based on their extremely feeble interaction strength with ordinary matter that allows them to probe phenomena that are otherwise not accessible. Examples for that are the inner engines of core-collapse supernovae, gamma-ray bursts, active galactic nuclei, but also the interior of the Sun and the Earth. Neutrinos are messengers from the inner space of particle physics and the outer space of astrophysical phenomena and the universe. The group has contributed to these topics in the areas described in the following sections.

2. Neutrino Oscillation Analysis

Solid evidence for neutrino oscillations was first established as rate effects in Kamiokande (for atmospheric neutrinos) and in GALLEX (for solar neutrinos). The initial results allowed a vast range of quadratic mass splittings and mixing angles. The situation has now been cleaned up and especially the results from SuperKamiokande, SNO and KamLAND lead to two well identified oscillation solutions, as it can be seen in global fits to all available data [1]. These results fit perfectly to a scenario where three massive neutrino generations exist in analogy to the three generations of quarks and charged leptons. However, this need not be true in principle and the LSND experiment has indeed a signal which might be interpreted as a fourth neutrino state. Therefore, it is important to discuss the tension in the interpretation of data which is created by the LSND result [2].

3. The Potential of Future Reactor and Long Baseline Oscillation Experiments

Solar and atmospheric neutrino oscillations established finite neutrino masses which allow future experiments where the baseline and energy are optimized. This will lead to precision oscillation physics if neutrino sources are available which are under experimental control in order to avoid systematic limitations due to uncertainties in the produced flux and spectrum. Future reactor and accelerator long baseline experiments are such sources and it is very important to study the potential of possible setups in order to identify the best strategies. The aim of precision measurements is to precisely measure the leading oscillation parameters and to identify generic three flavour effects which are controlled by the small mixing angle θ_{13}. The Chooz experiment provides so far only a limit $\sin^2 2\theta_{13} < 0.15$ and it is very important increase the sensitivity by an order of magnitude, since most mass models predict θ_{13} in that range. Therefore new reactor experiments [12], like Double Chooz [7] with identical near and far detectors are planned. New reactor experiments would also allow to answer detailed questions which are connected to the spectrum of neutrinos of a nuclear reactor [8]. The quest for improved reactor experiments has also triggered new ideas, like the proposal to use directional information in a liquid scintillator to statistically separate two simultaneously running reactors [9], which could in the long run lead to even better measurements.

New reactor experiments are very important even if they only improved the limit for θ_{13}. The point is that this would imply that a new mechanism (flavour symmetry) which would be capable of explaining its small value. However, there are good reasons to expect θ_{13} within the reach of the next generation of experiments which makes it possible to measure leptonic CP violation. A very important point is here the synergy between future long baseline and reactor experiments. These experiments are not only complimentary in terms of the measured oscillation channels, but they provide rather different information such that the combined analysis is much more than the addition of statistics [5,3,4,6,10,11]. In general, future precision oscillation experiments allow to address very interesting issues in flavour physics [13].

The exploration of future oscillation experiments requires various tools. The GLoBES software package [14,15] was developed to allow realistic simulations where three flavour oscillation effects, MSW matter effects, various channels and backgrounds as well as detector properties are included. This powerful tool allows to get realistic assessments of future experiments, but systematic expansions of the three flavour oscillation probabilities [16] are necessary in addition in order to allow an analytic understanding of the high-dimensional parameter space.

4. Neutrino Masses, Flavour Symmetries and Lepton Number Violation

The aim of precise neutrino mass measurements is to understand the flavour structure behind it which may ultimately lead to an understanding the origin of flavour. Examples of such studies are [17,18]. Most mass models predict neutrino properties at high energies, typically at the GUT scale at about 10^{16} GeV. These initial predictions are subject to quantum corrections which can change the mass spectrum, the mixing angles and the leptonic CP phases [20,21]. Renormalization group effects may even resurrect or eliminate mass models which are considered excluded or viable without these quantum corrections [19].

Study of the neutrino-less double beta decay and searches for the manifestation of the neutrino mass in ordinary beta decay are the main sources of information about the absolute neutrino mass scale, and the only practical source of information about the charge conjugation properties of the neutrinos. It is therefore important to study the role of neutrino-less double beta decay experiments and direct searches for neutrino mass [22].

Besides neutrino masses there exist very good reasons to expect further new physics beyond the standard model of particle physics to be discovered within the coming years. Lepton flavour violation is in many of the studied scenarios a natural consequence, which leads to interesting implications for neutrino oscillation experiments. In fact, a combined analysis of oscillations and lepton flavour violation becomes in general necessary [23].

References

[1] M. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle,New J. Phys. **6** (2004) 122

[2] T. Schwetz, proceedings of the International Workshop on Astroparticle and High Energy Physics, October 14 - 18, 2003, Valencia, Spain

[3] W. Winter, Phys. Rev. **D70** (2004) 033006

[4] M. Lindner, proceedings of the International Workshop on Astroparticle and High Energy Physics, October 14 - 18, 2003, Valencia, Spain

[5] M. Lindner, proceedings of the International Workshop Neutrino Oscillations in VEnice - NOVE, December 3-5, 2003, Venice, Italy

[6] P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, Phys.Rev. **D70** (2004) 073014

[7] F. Ardellier *et al.*, "Letter of intent for Double Chooz: A search for the mixing angle theta(13)", hep-ex/0405032.

[8] P. Huber and T. Schwetz, Phys.Rev. **D70** (2004) 053011

[9] P. Huber, M. Lindner and T. Schwetz, JHEP **0502** (2005) 029

[10] P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, hep-ph/0412133.

[11] P. Huber, M. Lindner and W. Winter, hep-ph/0412199.

[12] K. Anderson et al., "White paper report on using nuclear reactors to search for a value of theta(13)", APS study group report, hep-ex/0402041.

[13] S. Antusch, P. Huber, J. Kersten, T. Schwetz and W. Winter, Phys. Rev. **D70** (2004) 097302

[14] P. Huber, M. Lindner and W. Winter, "Simulation of long-baseline neutrino oscillation experiments with GLoBES", hep-ph/0407333, to appear in Comp. Phys. Comm., http://www.ph.tum.de/~globes.

[15] P. Huber, M. Lindner, T. Schwetz, M. Rolinec and W. Winter, proceedings of the 21st International Conference on Neutrino Physics and Astrophysics (Neutrino 2004), College de France, Paris, June 14-19, 2004, Paris, France

[16] E. K. Akhmedov, R. Johansson, M. Lindner, T. Ohlsson and T. Schwetz, JHEP **0404** (2004) 078

[17] S. Choubey and W. Rodejohann, hep-ph/0411190.

[18] R. N. Mohapatra *et al.*, "Theory of neutrinos", APS study group report, hep-ph/0412099

[19] C. Hagedorn, J. Kersten and M. Lindner, Phys. Lett. **B597** (2004) 63

[20] J. Kersten, proceedings of the 12th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY04), June 17-23, 2004, Tsukuba, Japan.

[21] M. Lindner, proceedings of SEESAW25, international conference on the see-saw mechanism, Institut Henri Poincar, 10-11 June 2004, Paris, France.

[22] C. Aalseth *et al.*, hep-ph/0412300.

[23] T. Ota and J. Sato, AIP **721** (2004) 252