NEUTRINO PHYSICS : AN OVERVIEW

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1 Introduction

"The neutrino is the smallest bit of material reality ever conceived of by man", Cowan and Reines stated in 1956 [1] after their discovery of the particle which eventually led to the award of the Nobel Prize in 1995. More than 40 years after the epic experiment, the fundamental properties of the neutrinos, namely their masses and mixings, remain unknown. The "Standard Model" of particle physics simply "sets" the neutrino masses to be identically zero, but there is no compelling and profound physics reasons why it should be so (as compared to the masslessness of the photons being dictated by gauge invariance). The Standard Model neutrino therefore has no mass, no electric charge, half unit of spin, and only interacts via weak interactions. There are three families of neutrinos ($\nu_{\rm e}, \nu_\mu$andν_τ with their antiparticles, and only left-handed neutrino states are known to exist.

Neutrino masses and mixings among the three families, if they exist, will have far-reaching consequences in particle physics, astrophysics and cosmology [2]. In general, the "Grand Unified Theories" (GUTs) (model theories to unify strong, electromagnetic and weak interactions) predict a non-zero neutrino mass. Inversely, the knowledge of the neutrino masses among the three families will reveal much the structures of GUTs. In the opposite domain, massive neutrinos will have important bearings on the structures and compositions of the Universe and in particular, the "Dark Matter Problem". Therefore, the neutrinos provide a natural link between particle physics and cosmology, the physics of the very small and the very big length scale.

In addition, neutrinos can also serves as probes to study other physics. Accelarator neutrinos have been used to study nuclear physics, electroweak physics and QCD (theory of strong interactions). They provide cleaner signatures and easier interpretations of the results. Neutrinos from supernovae and other astrophysical sources, being directly from the interior, are good probes to provide direct access to the internal mechanism and structures of the objects..

2 Neutrino Physics and Astrophysics Experiments

The experimental investigation of the fundamental neutrino properties is one of the great frontiers in particle physics [3]. The experimental challenges originate from the fact that neutrinos only interact weakly with matter, and therefore techniques which can lead to construction of massive detector must be developed. The typical range of cross section of neutrino interaction on matter is shown in Figure 1, as compared with γp (electromagnetic) and πp (strong). For instance, nuclear power reactor produces an abundant supply of electron antineutrinos, and the cross section of their interactions with proton at the typical energy of 2 MeV is 6×10^{-44} cm^2 (or 10^{-5} fermto-barns!), corresponding to a mean free path of 250 light years of water !

A wide spectrum of pioneering techniques have been deployed in neutrino experiments. They cover a large range of complexities, locations, manpower and budget. The experimental efforts are ofter inter-disciplinary, involving input from particle physics, nuclear physics, chemistry, astronomy, astrophysics and cosmology. As examples, some of the frontiers being extended by neutrino experiments include:

- big - pilot studies are under way to prepare for "neutrino telescopes" which will have an effective detector size of 1 km^3;
- low count rate - the radiochemical gallium experiments are sensitive to one interaction per day from the solar neutrinos on 30 tonnes of gallium (or 10^{29} gallium atoms);
- low background - the target materials used in next generation of solar neutrino experiements have to be free of the radioactive ^{4}0K, ^{238}U and ^{232}Th contaminations to a level of 10^{-16} g/g ;
- slow - the 10^{20} half-life ranges measured in double beta experiments are the slowest process observed in nature;
- fine-grained - one ton of nuclear emulsion target with 1 μm resolution have been exposed in a accelerator neutrino beam over an extended period of two years.

Intense experimental efforts world-wide are being carried out on the investigations of the fundamental neutrino properties. The major lines include:

1. **Direct Kinematical Measurements** : The detailed shape of the electron spectra near the end points in nuclear beta decay

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z+1}) + \mathrm{e^-} + \bar{\nu}_{\mathrm{e}} ,$$

is sensitive to the electron neutrino mass at the 10 eV range. Similarly, information on the masses of $\nu_\mu$andν_τ can be obtained via the decays of π and τ, respectively.

2. **Double Beta Decay** : The lepton number violating process of neutrinoless double beta decay

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z+2}) + 2\mathrm{e^-} ,$$

is sensitive to both neutrino masses and mixings.

3. **Neutrino Oscillation** : If neutrino has mass, it can be transformed from one family to the other (e.g. $\nu_{\mathrm{e}} \rightarrow \nu_\mu$) as it propagates through space. Experimental searches of such phenomenon (neutrino "oscillations"), have been performed with neutrinos from the nuclear reactors, particle acceleratos, from the sun as well as the atmosphere, based on neutrinos with energy ranging from O(1 MeV) to O(10 GeV).

4. **Neutrino Astronomy** : Neutrinos from supernova SN1987a have been observed. At present, numerous big detectors located deep underground are capable of detecting supernova neutrinos. In addition, there are R&D efforts using ocean and lake water or the Antarctic ice as targets, whose aim is to identify high energy neutrino sources from astrophysical objects, thereby opening a window of observation of the Universe.

Out of these efforts, there are at present a few anomalous results which cannot be explained by standard physics :

1. **Dark Matter Problem**: There are mounting evidence that most of the masses of the Universe are "non-baryonic" (not the ordinary matter composing of protons and neutrons) which do not emit electro-magnetic radiation but make their existence felt only via gravity. Neutrino is one of the candidates for these "Dark Matter".

2. **Solar Neutrino Puzzle** : Neutrino fluxes from the Sun measured on Earth are less than the expectations from solar models. These results can be explained in terms of neutrino oscillations.

3. **Atmospheric Neutrino Anomaly** : Neutrinos are also created when cosmic rays hit the upper atmosphere. Neutrino flux measurements at ground level are less than predictations from models, and can again be interpreted as neutrino oscillations.

4. **LSND Positive Results** : An accelerator neutrino experiment LSND at the Los Alamos Laboratory claims to have observed neutrino oscillation in the $\nu_\mu \rightarrow \nu_e$ channel.

The present and next generation of neutrino experiments will put some of these anomalous results to further stringent tests. As an example to illustrate the scale of experimental efforts, the Super-Kamiokande experiment is located in an underground laboratory under 900 m of rock in central Japan. It is made up of 50 kilo-tons of purified water viewed by about 13000 50-cm diameter photo-multiplier tubes. The detector has been operational since 1996 and will collect high statistics data which may enable crucial clarifications of the solar and atmospheric neutrinos anomalous results. In parallel, an accelerator neutrino beam is now being constructed at the KEK-Laboratory in Japan. When completed, a "long baseline" neutrino oscillation experiment can be performed where the neutrinos will traverse a distance of 250 km from the source to the Super-Kamiokande detector. Besides neutrino physics, the experiment will also conduct searches on proton decay.

3 Neutrino Activities in Taiwan

Research in neutrino experiments started in Taiwan in 1996 [4]. The principal objectives of the neutrino group are to initiate a program in experimental neutrino physics and astro-particle physics, as well as to build up a qualified experimental team for future projects.

The eventual goal is to conduct a world-class experiment in Taiwan. A good local research program is complementary to the participation of international projects elsewhere, and is essential to the solid foundation of international collaborative basic research in the country. As the field grows and matures, the community has to acquire the experience of conceiving, formulating, fighting for, and then implementing and coordinating a big project. A local program also serves as a base for training young students and scientists, as well as promoting the discipline of large-scale basic research to the general public.

Given the above implications and considerations, the field of choice is reactor neutrino. There are operational power reactors in Taiwan. The mountainous landscape dotted with mines and tunnels makes the construction of an underground laboratory conceivable.

A collaboration has been built up to conduct neutrino physics experiment in Taiwan. At present, the Collaboration comprises more than 40 scientists with diversified expertise from Taiwan (Academia Sinica, Institute of Nuclear Energy Research, National Taiwan University, National Tsing Hua University and Taiwan Power Company), China (Institute of High Energy Physics at Beijing, Nanjing University, Shandong University, University of Science and Technology at Hefei) and the United States (University of Maryland).

The Collaboration has been intensely pursuing efforts in two fronts : 1) an R&D program on liquid scintillator, and 2) the preparation of a pilot experiment using a detector O(1-ton) target mass to be put inside the Nuclear Power Plant II near Chin Shan. These projects will serve important learning exercise and team-building efforts for our new Collaboration. It is expected that this experience will equip us with the necessary experimental techniques in this field and will help us to build up a qualified team to make major contributions in future projects. Some physics issues like neutrino cross sections on electrons and nucleii can also be addressed. In the near future, we will start doing the homework on the physics studies, conception and formulation of the "next" project, a possibility of which would be along the line of long baseline neutrino oscillation using reactor neutrinos.

4 Outlook

Neutrino physics and astrophysics is an exciting and active field. A wide spectrum of pioneering techniques are deployed in experiments, and there are much room for surprises in their outcomes. There may be some "hints" that new physics may round the corner in this sector. The present generation of experiments will put these "hints" to further strutiny, and will define the future landscape of the field.

A collaboration comprising of physicists from Taiwan and mainland China have been built up to perform experiments using reactor neutrinos in Taiwan. Both the science as well as the collaborative method of pursuing it are new to Taiwan (the equivalence of playing symphony music in an orchestra). The importance of the outcomes of such an "experiment" will lie beside, if not beyond, neutrino physics.

References

[1] F. Reines and C.L. Cowan, Phys. Rev. **90**, 492 (1953);
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[2] For an overview on the subject of neutrino physics, see, for example, "Physics of Massive Neutrinos", 2nd Edition, Felix Boehm and Petr Vogel, Cambridge University Press (1992).

[3] For an overview on the current status and frontiers in neutrino physics and astrophysics, see, for example, "Procs. of the 17th Int. Conf. on Neutrino Physics and Astrophysics, Helsinki 1996", eds. K. Enqvist, K. Huitu and J. Maalampi, World Scientific (1997).

[4] "The Starting-Up of a Neutrino Project in Taiwan", C.Y. Chang, S.C. Lee and H.T. Wong, in *Procs. of XVI Int. Workshop on Weak Interactions and Neutrinos 1997*, to be published in Nucl. Phys. (Procs. Suppl.) **B** (1997).

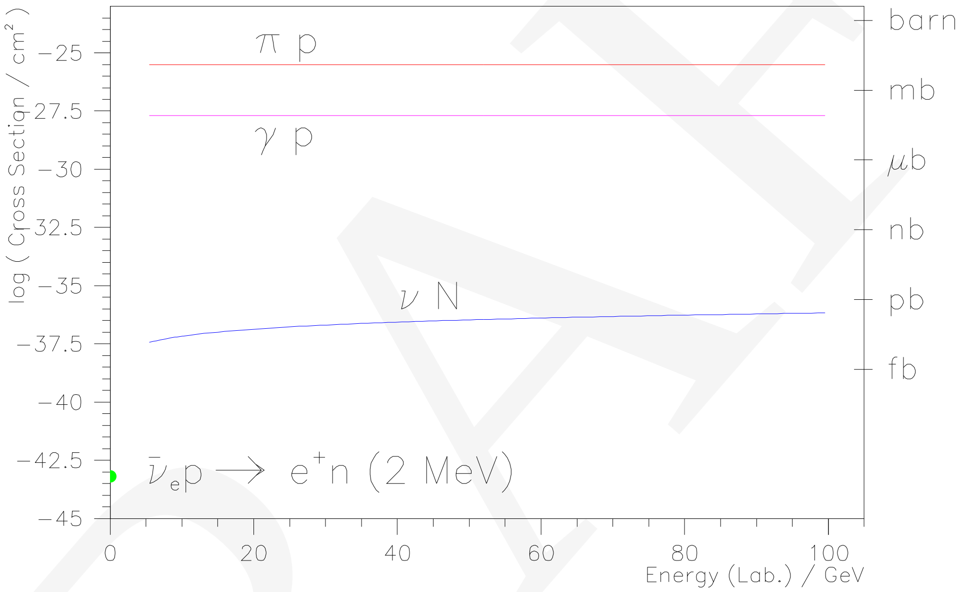

Figure 1: Typical range of cross sections for neutrino interactions, as compared to typical strong (πp) and electromagnetic (γp) cross sections.