Proposal: EXONO
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A Pilot EXperiment On Neutrino Oscillation (EXONO)

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Abstract

The nuclear power reactors of Taiwan Power Company can potentially provide the most ideal and powerful sources of anti-neutrinos($\bar{\nu}_e$) for the searches of neutrino oscillation. Experimental results may lead to definitive answers to questions on fundamental properties of neutrinos, as well as to the cosmological puzzles such as the deficit of solar neutrinos and the properties of dark matter. We propose to carry out a pilot experiment to study the feasibility of a full scale neutrino oscillation experiment with the $\bar{\nu}_e$'s provided by the Power Plant-II of Taiwan Power Company.

1 Introduction

In order to save the quantum statistics and the law of energy conservation from bankruptcy in β-decay, Wolfgang Pauli postulated the existence of the neutrino in 1930. Although, at that time, the experimental data were there to provide perfect evidence for its existence, it was Pauli who had the insight to suggest such a new particle. Neils Bohr, looking at the same data, was led to propose that conservation of energy, within the atom, is only statistically valid[1]. In his famous "Dear Radioactive Ladies and Gentlemen" letter, Pauli said that he had hit upon a desperate remedy to save the situation, ..., yet dared not to publish anything about his idea. He had, in fact, apologized to his friend by saying that he had done a terrible thing; he had postulated a particle which could not be detected[2]. The sense of desperation is understandable, because there were only three known elementary particles, p, e^- and the γ, at that time. Introducing a new particle was certainly not an ordinary thing. Today, 65 years later, the neutrino has not only been detected, but has also proven itself to be one of the most fascinating elementary particles in the field of particle and astrophysics. It has played an important role in shaping the concepts of modern physics. Yet many of its fundamental properties, such as mass, magnetic moment, flavour mixing, etc., normally considered to be the basics for an elementary particle, remain mysteriously unknown. There are a lot of persisting questions in cosmology and astrophysics, such as the deficit of solar neutrinos, the anomaly in the measured ratio of atmospheric neutrinos, and the nature of dark matter. These areas may directly or indirectly be related to the fundamental properties of the neutrinos: Do neutrinos have finite masses? Are the masses different for different flavours of neutrinos? Can neutrinos of different flavours mix?

Neutrino oscillation can effectively provide the most sensitive information on neutrino masses and flavour mixing. Since the nuclear power reactors of Taiwan Power Company in Taiwan can potentially provide the most ideal and powerful sources of anti-neutrinos ($\bar{\nu_e}$), we propose a pilot experiment to study the feasibility of a full scale EXperiment On Neutrino Oscillation (the EXONO proposal). With the $\bar{\nu_e}$'s provided by Power Plant-II of Taiwan Power Company, EXONO results may lead to definitive answers for the questions on fundamental properties of neutrinos, as well as on the cosmological puzzles as mentioned above. Organization of the proposal is given as follows:

Section 2: Physics

In this section we will review the problems related to fundamental properties of the neutrinos, concentrating on the deficit of solar neutrinos, the anomaly in the measured ratio of atmospheric neutrinos, and the status of dark matter.

Section 3: Weighing the neutrinos

In this section we will review the current progress on the measurement of neutrino mass.

Section 4: Neutrino oscillations

In this section we will review the relevance and current status of terrestrial neutrino oscillation experiments with respect to the solar neutrino problem, etc.

Section 5: Neutrino oscillation experiment in Taiwan (Proposal EXONO)

In this section we will discuss the reason, the scope and the initial collaboration of EXONO.

Section 6: The pilot experiment

In this section we will first describe the basic principles and the signature of signals. We will then discuss the selection of the liquid scintillator and ^{10}B loading. We will also show the Monte Carlo simulations on the acceptance of the e^+–related signals and the acceptance of the neutron-capture signals.

Section 7: The detector

In this section we will discuss the design of the detector, a prototype table top module, the event trigger and data acquisition, and the pulse shape discrimination (PSD).

Section 8: Data analysis and the anticipated results

Section 9: Background studies

Section 10: Work in progress and the anticipated achievements

Section 11: Equipment and budget

Appendix A: The deficit of solar neutrinos

Appendix B: Experimental status of neutrino oscillation

2 Physics

Over the past 30 years, there has been much excitement about "New Physics Effects", such as $\mu \longrightarrow e\gamma$, the light Higgs, terrestrial neutrino oscillations, 17 keV neutrinos, magnetic monopoles, fractional charged particles, etc. The great majority of these scientific speculations came and disappeared very quickly. Only a few of them have survived the test of time and eventually turned into major issues in modern physics, for instance: "The deficit of solar neutrinos", "The anomaly in the ratio of atmospheric neutrinos", and "The question of dark matter in the universe". In this section we will review the current status of these problems.

2.1 The deficit of solar neutrinos

It is well known that solar neutrinos have been detected by underground experiments, yet none of them has measured a solar neutrino flux as large as that predicted by the Standard Solar Model (SSM). As shown in Table I, new results on the measured solar neutrino flux from **SAGE**[3], **GALLEX**[4] and **Kamiokande**[5] all converge at about one-half the rates predicted by the SSM of Bahcall and Pinsonneault[6]. The discrepancy between experimental observation and the predictions of the SSM typically lies between 3 to 4 σ in significance, while the **Homestake**[7] Cl-Ar experiment sees only 29% of the predicted rate with a 6 σ significance. Since the ^8B neutrinos must have interacted in all of the experiments, it is very hard to reconcile all these measurements, especially with those of the ^7Be neutrinos, which created the persistent solar neutrino problem. In particular, a recent experiment by **GALLEX**[8], using artificial ν_e source from β decay of ^{51}Cr, has further confirmed the seriousness of the solar neutrino problem (see column 6 of Table I).

One of the most promising solutions is the Mikheyev-Simirnov-Wolfenstein (MSW) matter mixing mechanism, in which a solar neutrino (ν_e) mixes with ν_μ or ν_τ (or both) when traversing the sun[9, 10]. Hence solar neutrinos, the left handed ν_e, may turn into a sterile form which would not be sensitive to the underground detectors. According to MSW, ν_e's passing through matter 'feel' an extra effective potential

$$V_{eff} = G\sqrt{2}N_e$$

via charged current ν_e electron interactions. When the scatterings are coherent, the V_{eff} may engender significant changes in the 'masses,' which changes the mixing angles in the medium[11]. As shown in Fig. 1, when ν_e is produced in the solar core via weak interactions, where A = 2 E V $\gg A_R$:

$$\nu_e = \nu_1 cos\phi + \nu_2 sin\phi$$

Table I: The experimental and theoretical uncertainties are those quoted at 1σ. The total uncertainty is obtained by adding the quoted experimental and theoretical uncertainties in quadrature, and a SNU is defined as 10^{-36} events per target atom per sec.

Experiment	Homestake	Kamiokande	SAGE	GALLEX	^{51}Cr
Sensitive to ν_e	$^7Be,^8B$	^8B	All	All	$^7Be,^8B$
Observed (Unit)	2.28 SNU	0.49 %	73. SNU	79. SNU	104 %
Expt/SSM	0.29 (0.35)	0.49 (0.63)	0.56 (0.60)	0.60 (0.65)	1.04 $\pm$0.12
Δ (expt)	0.03 (0.04)	0.07 (0.09)	0.14 (0.15)	0.09 (0.10)	
Δ (theory)	0.12 (0.22)	0.14 (0.26)	0.05 (0.06)	0.05 (0.06)	
Δ (total)	0.12 (0.22)	0.16 (0.28)	0.15 (0.16)	0.10 (0.12)	
Significance	5.9 σ (3.0 σ)	3.2 σ (1.4 σ)	2.9 σ (2.5 σ)	4.0 σ (2.9 σ)	0.3 σ

it is practically ν_2 and follows the ν_2 curve with little oscillation. When A $\longrightarrow A_R$, in the resonance region, the oscillation is maximal. The neutrino beam becomes $\frac{1}{2}\nu_1, \frac{1}{2}\nu_2$ regardless of θ. As it travels toward the surface, the neutrino continues to follow the ν_2 curve, according to: $\nu_2 = \nu_\mu cos\phi + \nu_e sin\phi$. The ν_μ component increases, and it then becomes ν_μ at the surface for a small mixing angle, which causes the deficit of ν_e. Figure 2 shows the best fitted values of δm^2 and the degree of mixing, the $sin^2(2\theta)$. However, there is no evidence of neutrino oscillations in any field outside the astrophysics,[1] and it is clear that a terrestrial experiment with sensitivity covering the same δm^2 and $sin^2(2\theta)$ region of the solar neutrino experiments is 'desperately' needed.

The main reason for this proposal, EXONO, is to understand the solar neutrino problem. We will summarize the current progress of solar neutrino experiments in Appendix A.

2.2 The anomaly in the ratio of atmospheric neutrinos

Atmospheric neutrinos arise from the decay of secondary pions, kaons, and muons produced by collisions of primary cosmic rays with oxygen and nitrogen nuclei in the upper atmosphere. For energies less than 1 GeV, all the secondaries decay and neutrinos

[1] Except in the recent results of LSND to be discussed in later sections.

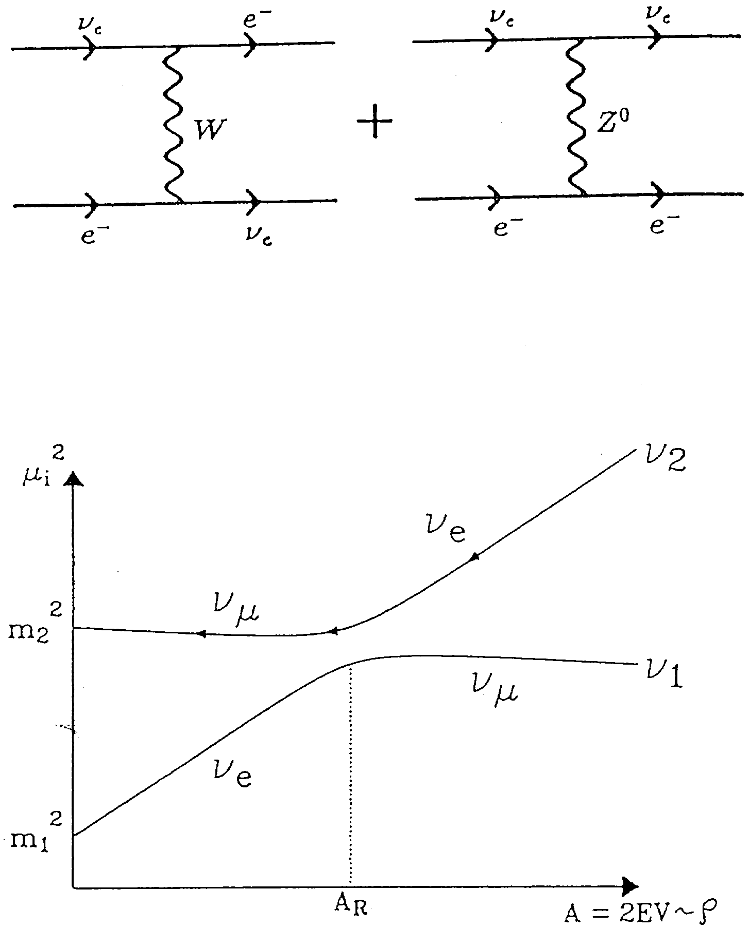


Figure 1: The MSW effect. a) Feynman diagrams describing neutrino interactions with electrons in matter. The $W^{\pm}$ exchange diagram is unique for ν_e. b) Via weak interactions, ν_e is produced in the solar core, following the ν_2 curve. In the resonance region, the oscillation is maximal and the neutrino continues to follow the ν_2 curve. It then becomes ν_μ at the surface for a small mixing angle.

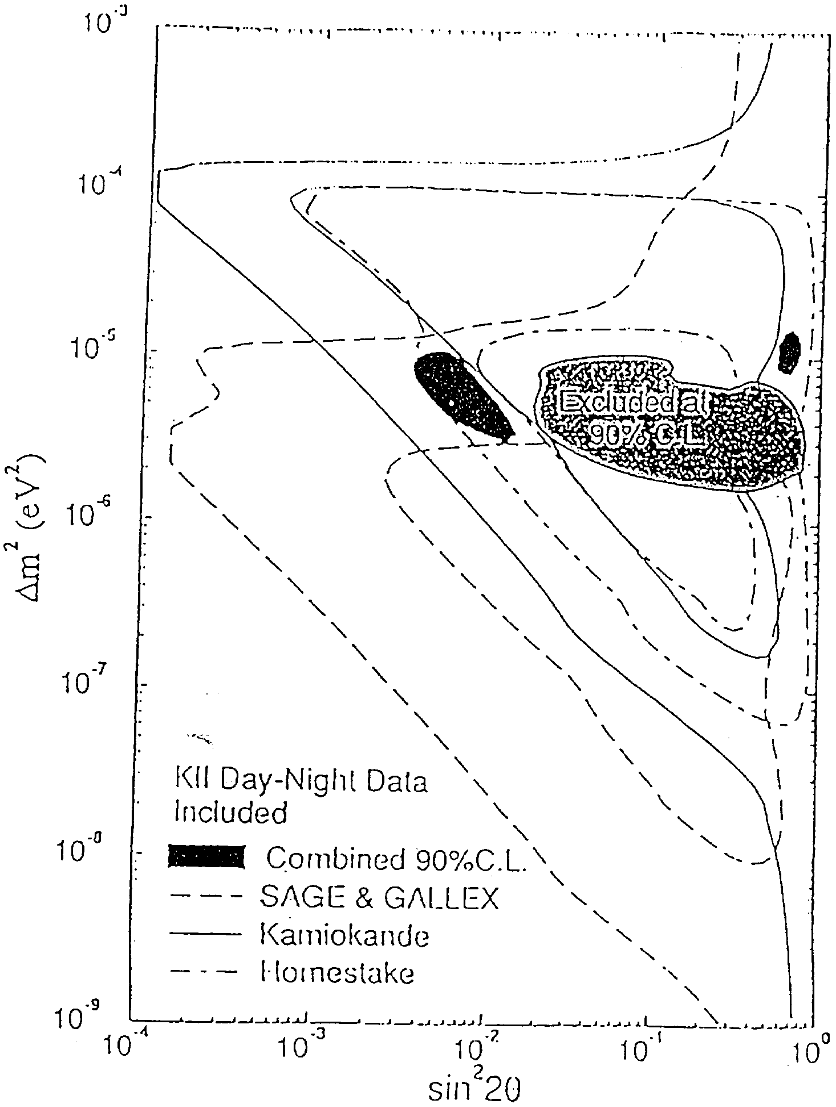


Figure 2: Regions of MSW parameter space allowed by the recent solar neutrino experiments

Table II: Ratio of ratios, R, as observed in different experiments

Experimnent	Exposure(kton-year)	R
Kamioka[12]	6.18	$0.60 \pm 0.06 \pm 0.05$
IMB[14]	7.7	$0.54 \pm 0.05 \pm 0.12$
Frjus[15]	1.56	$0.87 \pm 0.16 \pm 0.08$
Nusex[16]	0.40	0.99 ± 0.35
Soudan 2[17]	1.	$0.69 \pm 0.19 \pm 0.09$

are produced, i.e., primary cosmic rays + air $\longrightarrow$ hadronic showers ($\pi^{\pm}, K^{\pm}$, etc.). π or K will decay:

$$\pi^+(K^+) \longrightarrow \mu^+ + \nu_\mu$$

followed by

$$\mu^+ \longrightarrow e^+ + \bar{\nu_\mu} + \nu_e$$

Consequently one expects the ratio:

$$\phi(\nu_e) : \phi(\nu_\mu) = 1 : 2$$

or:

$$r = \frac{\nu_e + \bar{\nu_e}}{\nu_\mu + \bar{\nu_\mu}} \approx 0.5$$

in this energy range. Detailed Monte Carlo calculations including the effects of muon polarization, give $r \sim 0.45$[12, 13]. To avoid systematic errors, the ratio:

$$R = \frac{(\nu_\mu/\nu_e)_{data}}{(\nu_\mu/\nu_e)_{MonteCarlo}}$$

was determined. Theoretically, one expects that R = 1. As shown in Table II, the observed R seems to be persistently equal to 0.5. Oscillations of ν_μ into ν_τ are generally invoked to explain this discrepancy. Assuming that the base line is less than 50 km, and neutrino energy ranges from 0.1 to 1 MeV, we anticipate that $\delta m^2 > 10^{-3} eV^2$. If the atmospheric neutrino anomaly is resolved by the oscillations of muon neutrinos into tau neutrinos, this value of δm^2 is consistent with a tau neutrino mass relevant to the hot dark matter (which will be discussed in the next section) and supernova dynamics.

2.3 The question of dark matter in the universe

From measurements of the rotational curves of the spiral galaxies, we have:

$$\frac{m v_{escape}^2}{R} = \frac{GmM}{R^2}$$

hence:

$$v_{escape} \propto \sqrt{1/R}$$

where v_{escape} is the escaping velocity of the measured object, G is the gravitational constant, and M is the total mass inside the orbit of radius R for the measured object.

There is evidence for a dark halo because we find that v_{escape} is constant in every case that observations extend to $R \gg h$, where $L(R) = L_o e^{-R/h}$ and $h \sim 4kpc$ for our Galaxy. In terms of the matter density ρ, we find:

$$\rho_{luminous} \sim 1\% \rho_{v_{escape}}$$

A popular version of the Big Bang Model is the Inflationary Universe, in which when $\rho = \rho_{critical}$ the universe will be closed. We define:

$$\Omega = \frac{\rho_{obs}}{\rho_{critical}}$$

which should be 1 for a closed universe. The observed values are:

$$\Omega_{luminous} \sim 1\%$$

$$\Omega_{\text{large scale pec. v flow}} \sim 30\%$$

$$\Omega_{BBN} \sim 0.015h^{-2} \text{ etc.}$$

Roughly speaking, as the length(h)/mass scale increases from that of individual galaxies, to small collections of galaxies, to large aggregates, and beyond, the amount of mass inferred from the dynamics increases while the luminosity does not. Thus, on larger and larger scales, there is more mass but not more "light", hence, the dark matter problems. Since there is no a priori reason that the universe should have chosen to reveal itself with (earth man's) visible light, the exact issue is quite confusion. It is clear that there are uncountable 'dark' matters. The question is what are the natures of the "dark" matters? Neutrino with a little mass is an ideal candidate because the universe is filled with primordial neutrinos just like the 2.7 degree photons. All one needs is neutrinos with a few eV of mass that would be sufficient to close the universe. In fact, one of the most important constraints on neutrino masses from cosmology and astrophysics is the limit

$$\sum m_i < 35eV.$$

If this limit does not hold, then there would be too much energy density in the present universe. See reference [18] for an excellent review on this issue.

To summarize, the tactic of weighing the neutrinos is not only a measurement of its fundamental properties, but is also 'desperately' needed for consistent answers to many important cosmological questions.

3 Weighing the neutrinos

The mass of the neutrino has been estimated based on the following types of observations:

Burst of neutrinos from supernovae.
Direct measurements (β and $\beta\beta_{o\nu}$ decays).
Neutrino oscillations.

In the following subsections, current progresses on these experimental measurements of neutrino mass are briefly discussed.

3.1 Burst of neutrinos from supernovae

Supernovae represent the endpoint or death of normal stellar evolution of stars. On the other hand, the energetic input of supernovae may influence the formation of new stars by compressing interstellar gas, resulting in the birth of neutron stars. In the formation of a neutron star, the core of the supernova which is about 1.4 times the mass of the sun, would be squeezed into an extremely dense object only 10-20 km across. For this to happen the core must lose about (2 to 3) x 10^{53} ergs of energy, of which only 1% takes the form of light. The remaining 99% is released in the form of neutrinos[19]. The $E_{average}/\nu$ is about 10 MeV. It is a truly remarkable fact that although the star may have lived for tens of billions of years, its core collapses in a second. It takes no more than a few seconds for the neutrinos to diffuse out. The spread of time of arrival of the neutrinos on earth can provide a measurement of the neutrino mass.

The first supernova (the SN1006) to be recorded as such was observed by Chinese astronomers in the eleventh century, during the Sun Dynasty. On February 23, 1987, SN1987a was observed. It corresponds to an event some 170,000 years ago, when an old star in the Large Magellanic Cloud exploded (See Fig. 3). The burst of neutrinos was observed both by Kamiokande[20] and IMB[14]. The time spread, as shown in Fig. 4, is less than 13 seconds. Since[22, 23]:

$$\Delta t_{emission} = \Delta t_{spread} - \frac{D}{2c}(\frac{m_\nu}{E_\nu})^2$$

where $\Delta t_{spread} = 13sec$, D = 50 kpc = 170,000 light year, we find that $m_\nu \leq 20eV$ when we assume that $\Delta t_{emission} = 0$. However, this is only an upper limit.

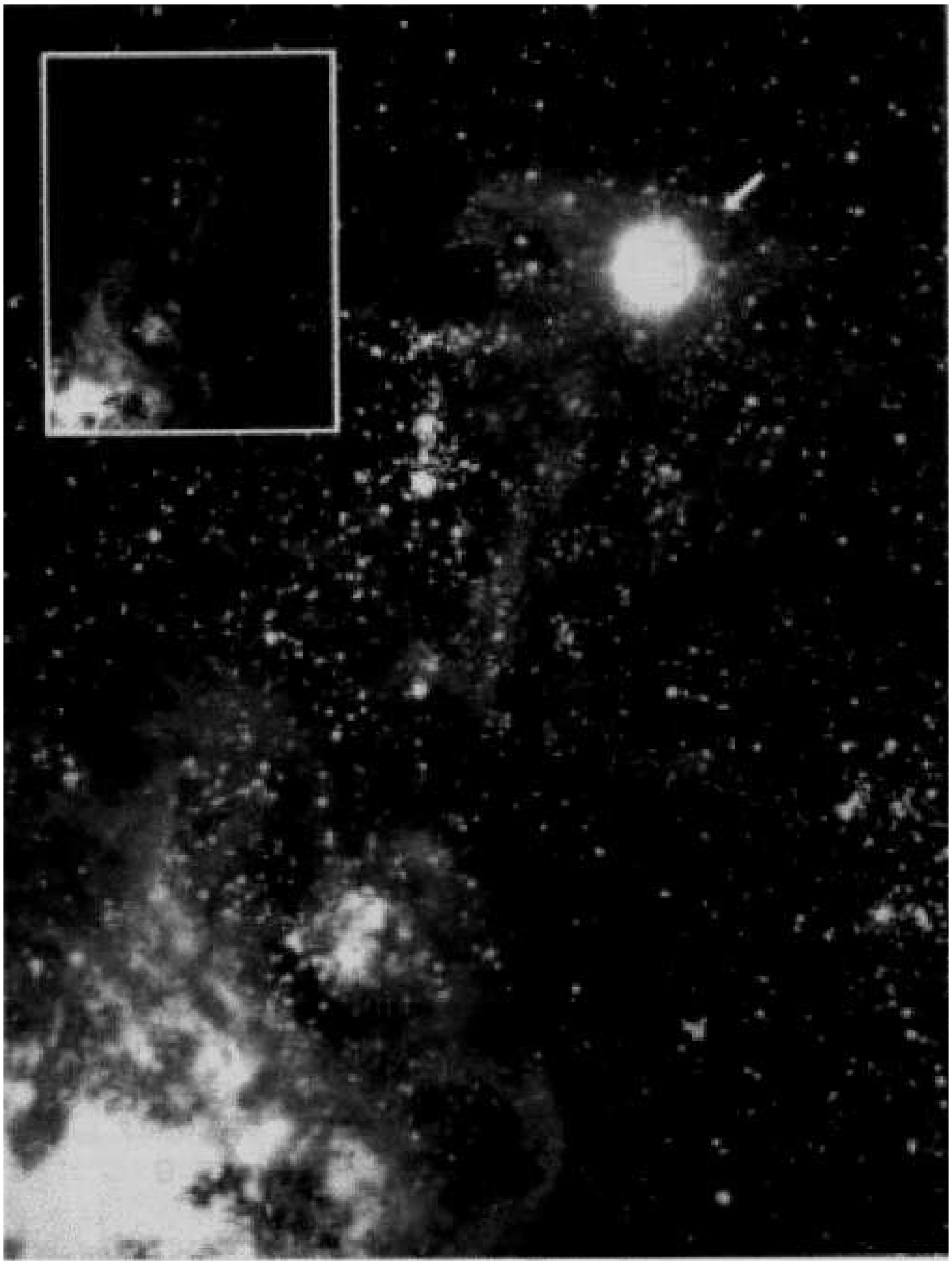


Figure 3: SN1987a, a star which exploded 170,000 years ago, was photographed by the Anglo-Australian Observatory on February 23, 1987. The arrow points at the bright spot of hot glowing gas in the Large Magellanic Cloud after the star's explosion, while the insert picture shows the same spot before explosion.

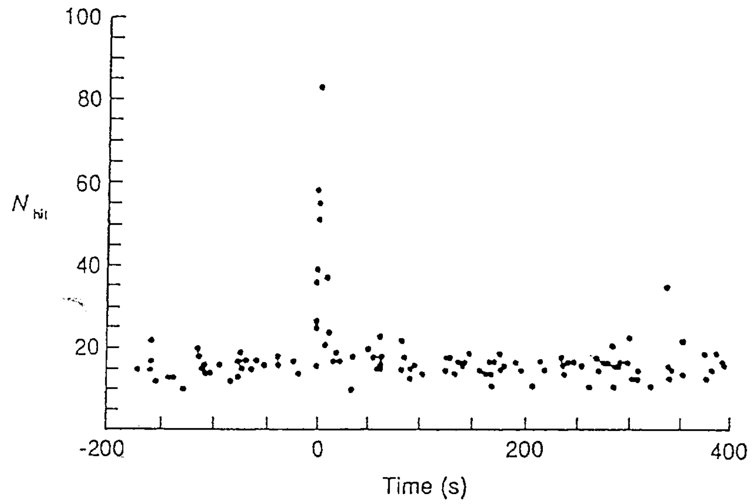


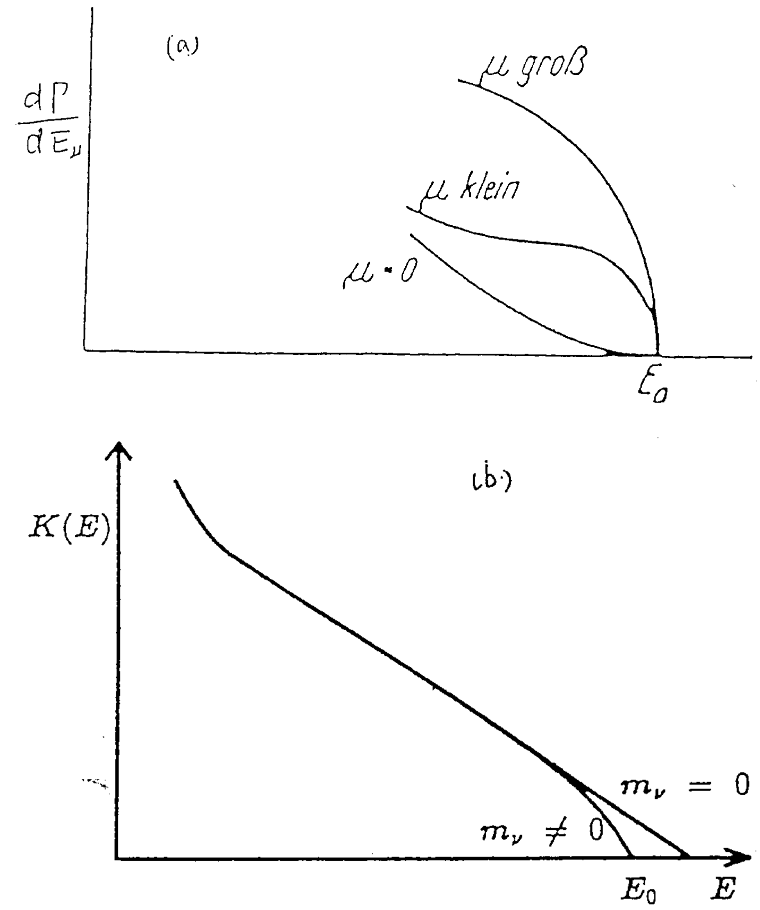
Figure 4: The number of photomultiplier hits (number of neutrino initiated events) recorded in Kamiokande II on February 23, 1987. Time 0 corresponds to 07:35 universal time.

3.2 Direct measurement

In 1934, after Pauli's postulation of the existence of the neutrino and the discovery of the neutron by Chadwick, Enrico Fermi formulated his famous Fermi theory of nuclear beta decay (the universal Fermi theory of weak interaction). Based on this theory, it is possible to tell the mass of the neutrino from the shape (see Fig. 5) of the beta spectrum near its high energy limit (the endpoint). Fermi was able to conclude that the closest resemblance to the empirical curves is shown by the theoretical curve for zero mass.

In practice, measurement of neutrino mass via nuclear beta decay is an extremely difficult task. As shown in Fig. 6, the insert on the right hand corner is the end point part of the energy spectrum of the electrons emitted in the beta-decay of tritium blown up by a factor of 2500. It corresponds to about one billionth of the total phase space. In addition, since the fraction of the spectrum affected by the finite neutrino mass behaves as in: $S(E) \propto p(E + m_e c^2)(E - E_o) \times \sqrt{((E - E_o)^2 - (m_\nu c^2)^2)}$, the result depends on $m^2_{\nu_e}$. The most recent measurement of $m^2_{\nu_e}$ employs a new type of low energy β spectrometer, the 'solenoid retarding spectrometer'(SRS), an electrostatic filter with a magnetic guiding field. Its latest result, $m^2_{\nu_e} = (-39 \pm 34 \pm 15) eV^2/c^4$, implies that $m_{\nu_e} < 7.2 eV/c^2$. Table III shows the current status on $m^2_{\nu_e}$ measurements, which are proving to all be negatives. The world average of $m_{\nu_e} < 5.1 eV/c^2$ at 95% CL.

Since neutrino mass can also be derived from the neutrinoless double beta decay, research in this field continues to grow. Some of the searches have pushed the limit of



Kurie plots for the cases $m_\nu = 0$ and $m_\nu \neq 0$.

Figure 5: a) The end point behaviours of nuclear β decay from Fermi's paper on his theory of beta decay. b) The Kurie plots for the cases $m_{\nu_e} = 0$, and $m_{\nu_e} \neq 0$.

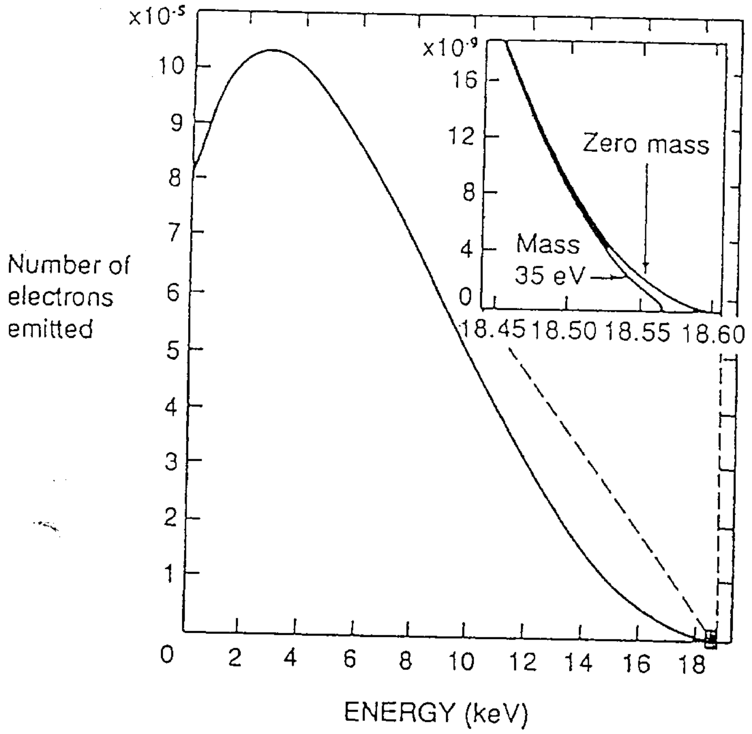


Figure 6: The energy spectrum of the electrons emitted in the beta decay of tritium. The insert shows the end point part of the spectrum magnified 2500 times. (W. Kündig, University of Zürich.)

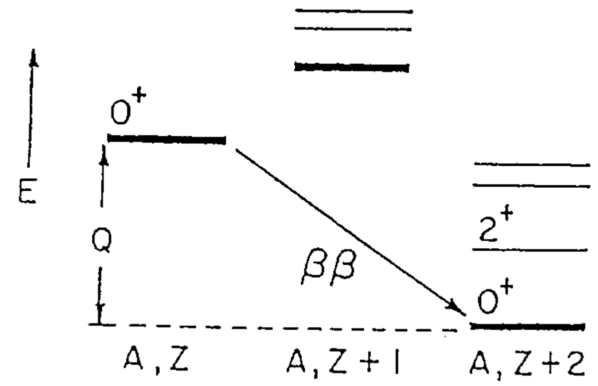
Table III: The $m^2_{\nu_e}$ from tritium β decays

Experiment	Sources	$m^2_{\nu_e}(eV^2)$ from best fit	m_{ν_e} Bound (eV) at 95% CL
INS, Tokyo	Cd Arach-t	$-65 \pm 85 \pm 65$	13 [1]
Zürich	OTS-t	$-24 \pm 48 \pm 61$	11 [2]
Los Alamos	t_2 gas	$-147 \pm 68 \pm 41$	9.3 [3]
Mainz	t_2 gas	$-39 \pm 34 \pm 15$	7.2 [4]
Livermore	t_2 gas	$-130 \pm 20 \pm 15$	7 [5]
INR, Moscow	t_2 gas	-18.5 ± 6	4.5 [6]

[1] H. Kawakami, et al , Phys. Lett. B256, 105 (1991).
[2] E. Holzschuh, et al. Phys. Lett. B287, 381 (1992).
[3] R.G. Robertson et al Phys. Rev. Lett. 67, 957 (1991)
[4] C. Weinheimer et al, Phys. Lett. B300, 210 (1993)
[5] W. Stoeffl et al Lawrence Livermore National Lab. Preprint.
[6] V. Lobashev 27th Int. Conf. HEP '94 Glasgow.

the effective Majorana neutrino mass below 1 eV, but no evidence of $(\beta\beta_{o\nu})$ reaction has been found.

Double beta decay is a second-order weak transition between nuclei of the same mass number and differing in Z by two units, while the single beta decay to the intermediate nucleus (with a huge increase in phase space, about a factor of 10^6) is only forbidden by energy conservation (see Fig. 7). Neutrinoless double decay $(\beta\beta_{o\nu})$ violates lepton num-



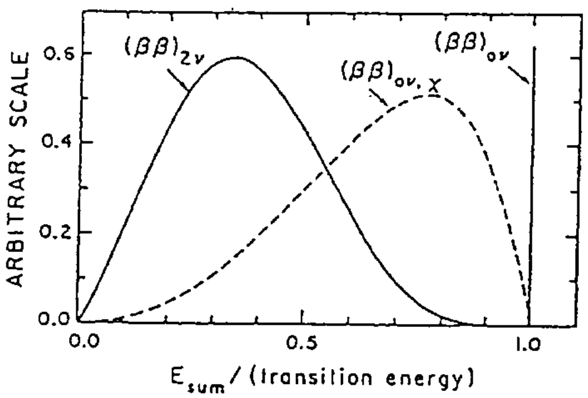


Figure 7: Energy levels for double beta decay nuclei.

ber conservation and requires that the neutrino and anti-neutrino be identical Majorana particles having finite mass. The experiment currently operating with the greatest sensitivity to $\beta\beta_{0\nu}$ is the enriched ^{76}Ge detector run by the Heidelberg-Moscow collaboration in Gran Sasso Underground Laboratory. The expected signal would be a narrow spike standing out from the background at the end point of the energy spectrum of the two beta particles. Their data show no significant peak. As a result, the $\beta\beta_{0\nu}$ half-life from their spectrum is :

$$T_{1/2}^{0\nu} > 5.1 \times 10^{24} y \ (90\% \text{ c.l.}),$$

with a corresponding neutrino mass limit:

$$(m_\nu < 0.68 eV).$$

The U.S. experiment (International Germanium Experiment(IGEX)), operating in the Homestake mine, is a second large enriched ^{76}Ge experiment. Another technique that has been quite successful in achieving sensitivity to $\beta\beta_{0\nu}$ is the 5 bar xenon TPC operated in the Gotthard Underground Laboratory by the Caltech- Neuchatel-PSI collaboration. Excellent reviews on current status on double beta decays can be found in reference [25]. It is clear that there is very little information on the mass of neutrinos that one can practically extract from these results.

4 Neutrino oscillations

As we have discussed in previous sections, the deficit of solar neutrinos and the anomaly in the ratio of atmospheric neutrinos all suggest strongly the evidence of finite neutrino mass and of neutrino flavour mixing. Although the former was interpreted in terms of MSW enhancement in flavour mixing while the latter suggested neutrino oscillation in vacuum, they are addressing different things, where neutrinos of different flavours oscillate back and forth via different mechanisms. However, the end result, that neutrinos must have finite mass, and neutrinos of different flavours must mix, is shared by both types of experiments. Thus, if the phenomena of neutrino oscillation were demonstrated in the laboratories where experimental environments could be controlled, it would provide convincing evidence of neutrino oscillation. Various terrestrial experiments have been tried, either with neutrino beams produced with accelerators or with anti-neutrinos produced in the nuclear reactors of commercial power plants. In this section we summarize the current progress with brief explanations.

The accelerators provide $\pi^{\pm}$'s through:

$$p + N \longrightarrow \pi^{\pm} + anything.$$

ν_μ and $\bar{\nu_\mu}$ are produced when π^+ decays:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

and

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu_\mu}.$$

This produces a beam with mixed flavours, and the energy of neutrinos ranges from tens of MeV to hundreds of GeV.

One looks for the oscillation:

$$a)\, \bar{\nu_\mu} \longleftrightarrow \bar{\nu_e}$$

or

$$\nu_\mu \longleftrightarrow \nu_e$$

and

$$b)\, \nu_\mu \longleftrightarrow \nu_\tau$$

followed by

$$\nu_\tau + A \longrightarrow \tau^{\pm} + B$$

$$\tau^{\pm} \longrightarrow \nu_\tau + anything$$