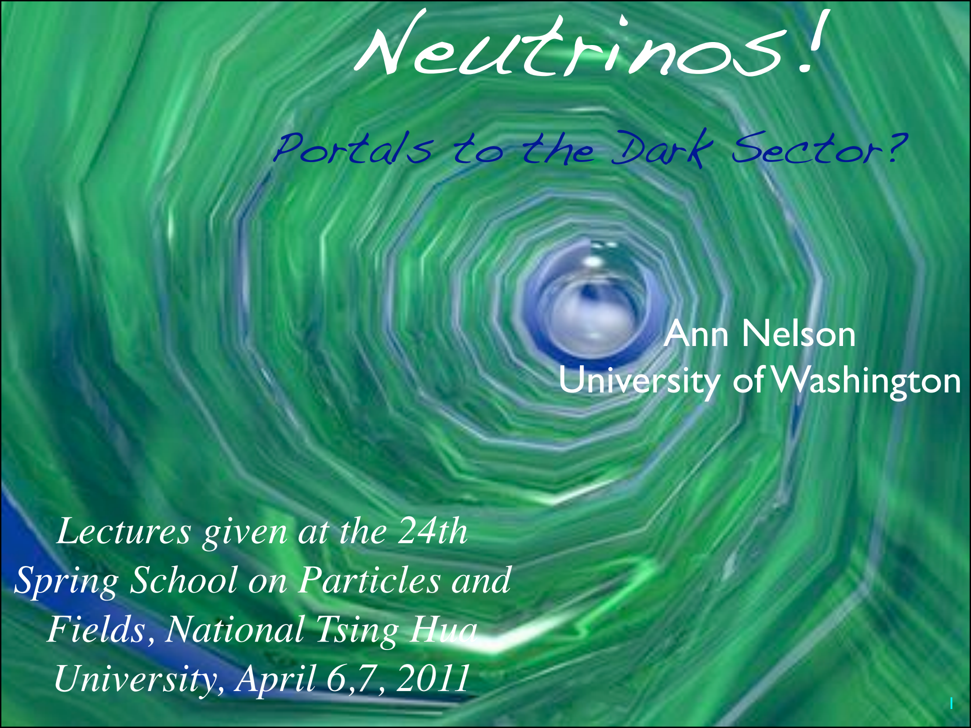


Neutrinos!

Portals to the Dark Sector?

Ann Nelson
University of Washington

Lectures given at the 24th Spring School on Particles and Fields, National Tsing Hua University, April 6,7, 2011

lecture I

Outline

- introduction to what we know about neutrinos
  - ➡ mass
    - ★ Majorana vs Dirac
  - ➡ mixing
  - ➡ oscillation
  - ➡ matter effects

} Introductory level

- critical open experimental questions
- the neutrino portal
- neutrinos in cosmology and astrophysics
  - ➡ effects of sterile neutrinos
  - ➡ dark energy coincidence and MaVaNs

} more advanced

ν Mass

Neutrinos in the Standard Model

- Standard Model was formulated without any neutrino mass, even though it was formulated after neutrino oscillation and neutrino mass had been suggested as a solution to the solar neutrino problem, and neutrino mass suggested as a solution to dark matter problem.

  Why leave out the neutrinos mass?

- Now that there is convincing evidence that neutrinos have tiny masses, neutrino mass has been incorporated into "the ν standard model(s)" in either of 2 ways.

Standard Model with Massless Neutrinos: helicity vs chirality

- Chirality = eigenvalue of γ_5.
  - ➡ Lorentz invariant measure of "handedness".
  - ➡ $P_L = \frac{1}{2}(1-\gamma_5)$, $P_R = \frac{1}{2}(1+\gamma_5)$
    - ★ Project out "left-handed" and "right-handed" fields
    - ★ chirality is Lorentz invariant
    - ★ for massless particles, (and only for massless states) chiral symmetry ⇒ chirality conservation
- Helicity = J·P
    - ★ for massless states (and only for massless states), helicity is Lorentz invariant
    - ★ for noninteracting particles, helicity is conserved

➡ for massless states (and only massless) chirality $\propto$ helicity

Chirality vs helicity, cont

- Massive states:
  - Chirality is Lorentz invariant, not conserved
  - Helicity is not Lorentz invariant, is conserved
- for state initially left chiral: <helicity>= - ½β *(for ν, $\beta \approx 1$)*
- for left handed helicity: <chirality>=-β
- left chiral **fields:** left chiral particles or right chiral antiparticles
- only left chiral fields are weak doublets
- in SM: neutrino part of weak doublet

$$\begin{pmatrix} \nu_{Le} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{L\mu} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{L\tau} \\ \tau_L \end{pmatrix}$$

- when ν was massless: "all ν's are are left handed (have negative helicity) and all $\overline{\nu}$'s are right handed (positive helicity)" (both are weak doublets)

ν mass in the Standard Model

Method I: Dirac

- same as any other fermion
- $\ell_{eL} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$ weak interaction doublet
- ν_{eR} weak interaction singlet. No gauge charges at all!
- h =Higgs doublet
- $\lambda_{\nu_e} < h > \overline{\nu}_e \ell_{eL} \Rightarrow m_{\nu_e} = \lambda_{\nu_e} < h >$
- no explanation why m_ν is so small compared with other masses

★ $m_\nu < 1$ eV ($\hbar$=c=1 units); m_e=0.5 MeV

More about Dirac mass

- For Dirac mass term, need ν_L and ν_R fields
- The neutrino and the antineutrino are different
- There are 4 particle states:
  - ➡ ν_L(weak doublet in massless limit),
  - ➡ ν_R (weak singlet in massless limit),
  - ➡ $\overline{\nu}_L$ (weak singlet in massless limit)
  - ➡ $\overline{\nu}_R$ (weak doublet in massless limit)
- Lepton number is conserved and distinguishes between ν and $\overline{\nu}$
- The ν_R field has no interactions other than through the mass term

Important note about "left" and "right"

- When referring to ***fields*** "L" and "R" refer to ***chirality***
- When referring to ***particles***, "L" and "R" refer to ***helicity***
- chirality and helicity coincide for massless particles and are opposite for massless antiparticles.
- Neutrinos are so ultra relativistic, so close to massless, that chirality and helicity almost coincide.

Majorana mass term

- For a neutral particle, if there is no conserved quantum number, the particle and anti particle may be the same
- $\overline{\nu}_R$ and ν_L transform the same way under Lorentz group
- Could have Lorentz invariant mass term $\nu_L\,\nu_L$ instead of $\overline{\nu}_R\,\nu_L$
- breaks lepton number
- ***breaks electroweak gauge invariance***

ν mass Method II:

Seesaw Majorana mass

- ν_R is gauge singlet field
- $\nu_R\ \nu_R$ Majorana mass term is gauge and Lorentz invariant
- If both Majorana and Dirac terms are present the ν mass terms may be written as a Majorana *mass matrix*:

$$\begin{array}{c|cc} & \nu_L & \overline{\nu_R} \\ \hline \nu_L & 0 & m \\ \overline{\nu_R} & m & M \end{array}$$

- m is just like the Dirac mass term and could have been written in usual way for Dirac term
- M is a Majorana mass term, breaking lepton number

$$\begin{array}{c|cc} & \nu_L & \overline{\nu_R} \\ \hline \nu_L & 0 & m \\ \overline{\nu_R} & m & M \end{array}$$

Seesaw continued

- Consider limit $M \gg m$ (motivated by GUTs)
- Diagonalize matrix perturbatively
- just like 2 state quantum system
- approximate eigenvalues: $M + \frac{m^2}{M}, \frac{-m^2}{M}$
  - ➡ sign of fermion mass does not matter
  - ➡ as M gets bigger, small eigenvalue gets smaller!
    - ★ $m_\nu \approx 0.1$ eV, $m \approx 100$ GeV $\Rightarrow M \approx 10^{14}$ GeV!
      - \- (at low energy, we can only determine $|m^2/M|$)

Effective Field theory

- Effective field theory
  - ➡ If a particle is too heavy to make, only see virtual effects
  - ➡ same effects can be approximately included in an effective (nonrenormalizable) local operator in the Lagrangian
    - ★ e.g. *4*-fermion operator in Fermi theory of weak interactions
- "Integrate out" heavy particles

$$\int D\Phi_{heavy}\, D\phi_{light}\, e^{i\int dx L(\phi,\Phi)} = \int D\phi_{light}\, e^{i\int dx L_{eff}(\phi)}$$

  - ➡ L_{eff} is sum of ∞ local operators
  - ➡ approximate L_{eff} with finite set of terms
    - ★ lowest dimension terms in L_{eff} dominate
    - ★ dimensional analysis, 3+1 spacetime dimensions: coefficient of dimension d term of order $(1/M)^{(d-4)}$, perturbatively expand in powers of (E/M)

Effective field theory and seesaw
Majorana mass

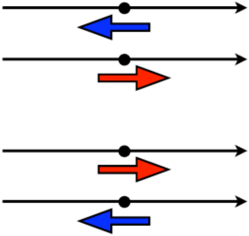
- Standard model is surely an effective theory
- Minimal Standard Model includes all terms to *d=4* (renormalizable)
  - ➡ *19* parameters
- next gauge invariant term in expansion: d=5 (nonrenormalizable)
  - ➡ $L_{eff} \supset c(h^2/\mathrm{M})\ \ell\ \ell\ (+h.c.)$
  - ➡ for $c=1$, M is scale at which approximation of keeping only low dimension terms in expansion of L_{eff} breaks down
  - ➡ L_{eff} breaks lepton number

Effective Field Theory of the seesaw

- Integrate out heavy ‘sterile’ singlet with Majorana mass and what do you get?
  - $L_{eff} \supset -(\lambda^2 h^2/M)\ \ell\ \ \ell$
  - nonrenormalizable dimension 5 term
  - unique dimension 5 term you can add to Standard Model with only Standard model fields
  - $h \rightarrow \langle h \rangle$: $L_{eff} \rightarrow$ into tiny Majorana mass term for ν
    - ★ $m_\nu = \lambda^2 \langle h \rangle^2 / M$
- ν has 2 components: left and right helicity
- Lepton number is broken⇒0 $\nu\ \beta\beta$ nuclear decay possible
  - ★ rate $\propto m_\nu^2$
- ν is its own anti particle.
  - ➡ weak interactions convert ν_L to charged lepton and ν_R to charged antilepton.
  - ➡ we usually refer to ν_L as the “neutrino” and its *CP* conjugate ν_R as “antineutrino”

Dirac v Majorana

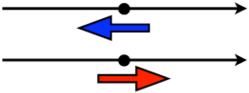
Dirac



	helicity	l^-	l^+
ν $L = 1$	L	1	0
	R	$(\frac{m_\nu}{E})^2$	0
$\bar{\nu}$ $L = -1$	R	0	1
	L	0	$(\frac{m_\nu}{E})^2$

……

Majorana



	helicity	l^-	l^+
ν	L	1	$(\frac{m_\nu}{E})^2$
$\bar{\nu}$	R	$(\frac{m_\nu}{E})^2$	1

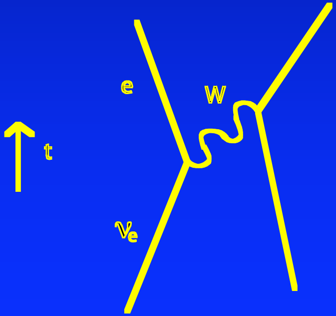
$$\boldsymbol{\nu = \bar{\nu}}$$

$$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$$

Weak Mixing and flavor violation

What do we know about neutrinos?

- Three types of neutrinos: e, μ, τ
  - Type determined by what lepton is produced



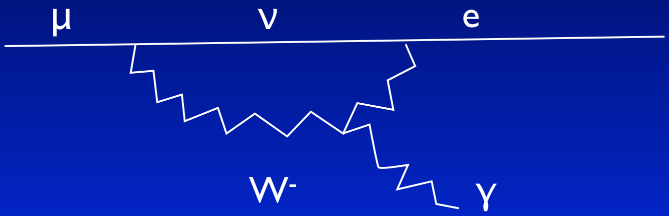
See the charged lepton produced!

Need enough energy:

$\nu_e \to e$ .511 MeV
$\nu_\mu \to \mu$ 105 MeV
$\nu_\tau \to \tau$ 1777 MeV

Lepton flavor

- Discovery of 2 types of neutrinos solved problem of why no $\mu \to e\gamma$



- Lepton flavor conservation (e,μ,τ numbers) a key piece of standard model

Early History of Neutrinos

“I have done a terrible thing. I have postulated a particle which cannot be detected.”-Pauli, 1930

- 1956 Neutrinos discovered by Reines and Cowan
- 1957 Neutrinos showed to have left handed helicity by Goldhaber et al
- 1961 Muon neutrino discovered at Brookhaven
- 1957-62 Pontecorvo, Sakata independently speculate that neutrino variety oscillates between electron and muon

Weak Interactions violate flavor in the quark sector

- quark doublets: $\begin{pmatrix} u_L \\ d_L' \end{pmatrix}, \begin{pmatrix} c_L \\ s_L' \end{pmatrix}, \begin{pmatrix} t_L \\ b_L' \end{pmatrix}$

Weak eigenstates

- quark weak eigenstates are not mass eigenstates

mass eigenstates

- weak quark mixing:

$$\begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{cs} & V_{tb} \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

- $V = V_{CKM}$
- $VV^{\dagger} = 1$
- mixing requires both up and down quarks to be massive, with non degenerate masses
- off diagonal CKM elements are small

Lepton mixing?

- Why not an analog of CKM matrix for leptons?
  - In minimal SM, with no ν_R field, ν's are massless and lepton flavor conservation is "automatic"
  - If neutrinos are massless, then can always make mass eigenstates = flavor eigenstates
  - What if ν's have tiny mass? lepton flavor violation should become unobservable as $m \Rightarrow 0$

PMNS matrix in Lepton sector

- lepton doublets: $\begin{pmatrix} \nu_{Le} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{L\mu} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{L\tau} \\ \tau_L \end{pmatrix}$
- lepton weak eigenstates are not mass eigenstates
- lepton mixing:
- $U=U_{PMNS}$
- $UU^{\dagger}=1$

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

- mixing requires neutrinos to be massive, and have nondegenerate masses
- observing mixing requires observing effects of nondegenerate neutrino mass

ν flavor oscillations

Kinematic Effects of mass

- Usually we observe effects of mass through the kinematic relation $E = \sqrt{p^2 + m^2}$
- Produce ν with $E >> \text{MeV}$
- m<eV

➡ $p \approx E - m^2/(2E)$

➡ $\Delta p < 10^{-15}$ MeV

➡ $\Delta x > 100$ m ! classical kinematic effects of mass not observable

Quantum Mechanical Effects of ν mass

- Neutrino wave packet is so ultra relativistic that it propagates with $\omega \cong k$
  - essentially no dispersion, distance traveled $x \cong t$
  - effect of mass on overall phase of wave packet: $e^{-i\frac{m^2 t}{2E}}$
  - flavor eigenstate produced in coherent superposition of mass eigenstates which acquire different phases as they travel
  - If only 2 ν's mix (e.g. $\nu_{\mu,}\nu_e$) simple formula for probability of flavor transition

$$P_{\mu\to e} = \sin^2(2\theta)\sin^2\left(\frac{(m_1^2 - m_2^2)x}{4E}\right)$$

mass vs flavor eigenstates

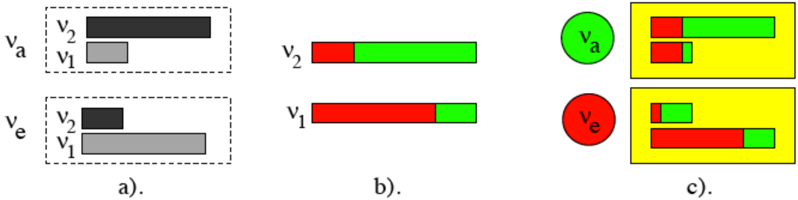


Figure 1: a). Representation of the flavor neutrino states as the combination of the mass eigenstates. The length of the box gives the admixture of (or probability to find) corresponding mass state in a given flavor state. (The sum of the lengths of the boxes is normalized to 1. b). Flavor composition of the mass eigenstates. The electron flavor is shown by red (dark) and the non-electron flavor by green (grey). The sizes of the red and green parts give the probability to find the electron and non-electron neutrino in a given mass state. c). Portraits of the electron and non-electron neutrinos: shown are representations of the electron and non-electron neutrino states as combinations of the eigenstates for which, in turn, we show the flavor composition.

from Smirnov
hep-ph/0305106

> 2 flavor mixing

- Probability of producing flavor *a* in a beam of flavor *b* at a distance *x* from the source

$$P_{ab} = \left| \sum_{j=1}^{n} U_{aj} U_{bj}^{*} e^{-i\frac{m_j^2 x}{2E}} \right|^2$$

$UU^{\dagger}=1 \Rightarrow$ no flavor change at $x=0$

- With >2 flavors, *U* can have a CPV phase, just like in quark mixing. For antineutrinos:

$$\overline{P}_{ab} = \left| \sum_{j=1}^{n} U_{aj}^{*} U_{bj} e^{-i\frac{m_j^2 x}{2E}} \right|^2 = P_{ba} \neq P_{ab}$$

A brief history of neutrino mass…

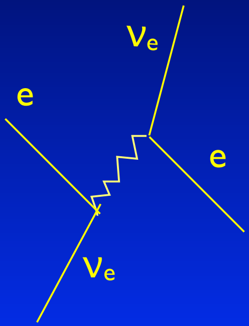
- The Standard Model (‘67-’68) - massless neutrinos
- 1967 - Homestake Experiment on solar neutrinos: “solar neutrino problem”
  - ➢ 50% depletion => need *very* small masses, large angles

    “Theoretical prejudice that θ_ν should be small makes this an unlikely explanation of [the solar neutrino problem].” - anonymous
  - ➢ Probably just astrophysics

effects of matter on oscillations

The MSW mechanism: effects of propagating though matter

- neutrinos propagate through matter
- matter is full of electrons
- forward scattering of electron neutrino
- additional phase for ν_e



Effective $\mathcal{H}$ for ν propatin

- in flavor basis: (simplified case of 2 neutrinos)
- ignore terms $\propto 1$, only can see $\Delta m^2 = m_2^2 - m_1^2$

$$H_{eff} = \begin{pmatrix} -\left(\frac{\Delta m^2}{4E}\right)\cos(2\theta) + V & \left(\frac{\Delta m^2}{4E}\right)\sin(2\theta) \\ \left(\frac{\Delta m^2}{4E}\right)\sin(2\theta) & \left(\frac{\Delta m^2}{4E}\right)\cos(2\theta) \end{pmatrix} \quad (+ \text{ terms} \propto 1)$$

- V is matter effect for electron neutrinos from electrons
- $V \propto$ density of electrons
- when diagonal terms are equal, resonant enhancement of mixing

Level crossing in the sun

- adiabatic conversion “start heavy, stay heavy”

from Smirnov
hep-ph/0305106

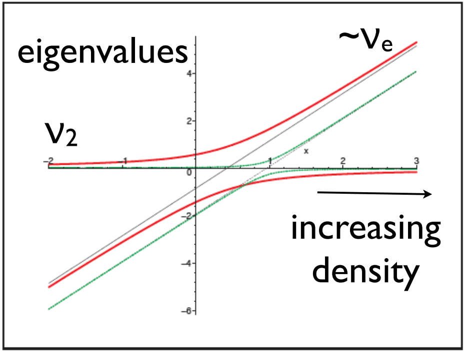


Figure 3: Level crossing scheme. Dependence of the eigenvalues of the Hamiltonian in matter, H_{1m} and H_{2m}, on the ratio $x \equiv l_\nu/l_0$ for two different values of vacuum mixing $\sin^2 2\theta = 0.825$ (solid, blue lines) and $\sin^2 \theta = 0.08$ (dashed, red lines).

More details of MSW

from Smirnov
hep-ph/0305106

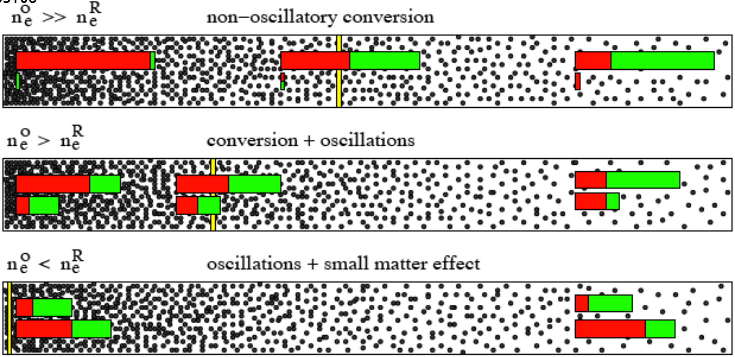
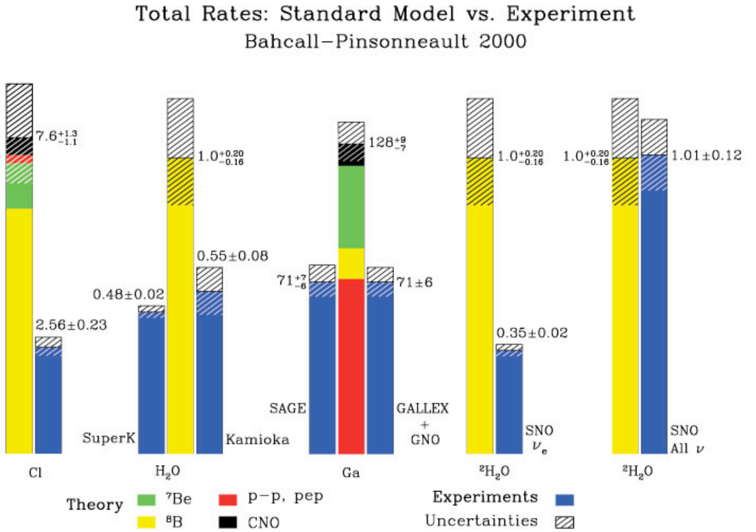


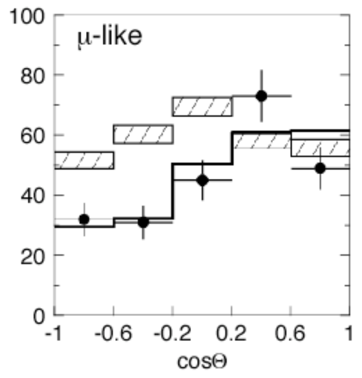
Figure 5: Adiabatic evolution of neutrino state for three different initial condition (n_e^0). Shown are the neutrino states in different moments of propagation in medium with varying (decreasing) density. The yellow vertical line indicates position of resonance. The initial state is ν_e in all the cases. The sizes of the boxes do not change, whereas the flavors (colors) follow the density change.

Fast forward to mid-90's…



‘98 Super-K Atmospheric ν’s

- Super-kamiokande sees atmospheric large atmospheric neutrino depletion



"All the News
That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

① Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

② . . . and collide with other particles . . .

③ . . . producing a cone-shaped flash of light.

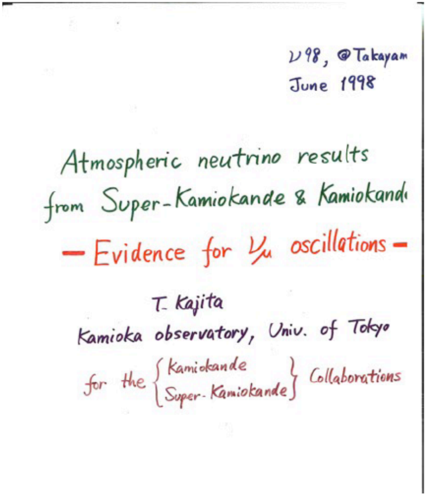
④ The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times



ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo

for the {Kamiokande
Super-Kamiokande} Collaborations

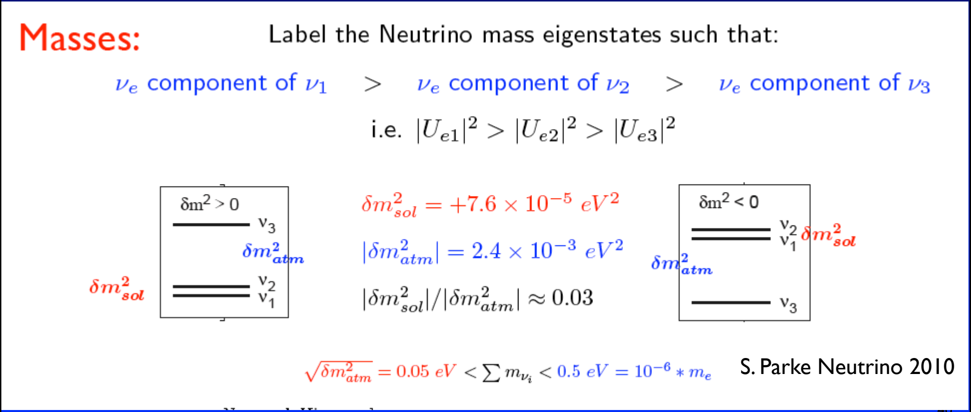
http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

Fast forward to ‘02-’03

- KamLAND and SNO
  - SNO: Sees neutral currents, missing neutrinos
  - KamLAND: Reactor experiment, controlled source => finds large angle MSW

2010 Summary of standard picture

- All confirmed results can be explained with 3 neutrinos



Masses: Label the Neutrino mass eigenstates such that:

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

i.e. $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

S. Parke Neutrino 2010

Mixing angles

Mixing Matrix:

not observable in oscillations

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV 15km/MeV

SNO/KamLAND
$|U_{e2}|^2$

Reactor/LBL
$|U_{e3}|^2(1-|U_{e3}|^2)$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

S. Parke Neutrino 2010

$$\frac{CC}{NC}|_{sno} \approx |U_{e2}|^2$$

Summary of history of neutrino mass theory

- Neutrinos are massless
- Neutrinos have small masses and small mixings, but they’re not relevant for anything
- Neutrinos have small mixings, and the MSW mechanism might explain the sun
- Neutrinos have one large mixing for atmospheric neutrinos, and the other two angles are small
- Neutrinos have two large mixings and one small mixing, and this time we really mean it.