Discovery of the Neutrino Mass-I

P1X* Frontiers of Physics Lectures
19-20 October 2004
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Outline

1. Introduction: the structure of matter
2. Neutrinos:
   2.1 Neutrino interactions
   2.2 Neutrino discovery and questions
   2.3 Neutrino oscillations
3. Atmospheric neutrinos
   3.1 Superkamiokande experiment
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4. The Solar Neutrino Puzzle:
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Motivation

Motivation for the Frontiers of Physics lectures:

1. Bring to your attention some of the most exciting fields of physics research at a level that can be easily understood
2. Help you to understand the link between undergraduate physics and front-line research.
3. Use some of the concepts learned in these lectures to improve understanding of undergraduate physics

Motivation for the Discovery of the Neutrino Mass lectures:

Neutrino physics: exciting recent discoveries have shown that neutrinos have mass, Nobel prizes for R. Davis and M. Koshiba in 2002.

References

Reading for the “Discovery of Neutrino Mass” lectures

1. “Detecting Massive Neutrinos”, E. Kearns, T. Kajita, Y. Totsuka, Scientific American, August 1999.
2. “Solving the Solar Neutrino Problem”, A.B. McDonald, J.R. Klein, D.L. Wark, Scientific American, April 2003.

Web references:

2002 Nobel Prize in Physics:

http://www.nobel.se/physics/laureates/2002/

Super-Kamiokande and K2K web-sites:

http://www.phys.washington.edu/~superk/

http://www.ps.uci.edu/~superk/

http://neutrino.kek.jp/

Sudbury web-site:

http://www.sno.phy.queensu.ca/

More on neutrinos:

http://wwwlapp.in2p3.fr/neutrinos/anhistory.html

1. The structure of matter

- Two types of particles:
  - Fermions (half-integer spin particles): make up the known matter and occupy "space" because of Pauli exclusion principle.

    Examples: quarks, protons, neutrons, electrons, muons, neutrinos, ...
  - Bosons (integer spin particles): carriers of the forces between fermions

    Examples: photons for electromagnetic interactions, W and Z bosons for weak interactions, gluons for strong interactions
- Fermions come in three families (why?, we don't know) and have antiparticles as well. One neutrino for every electron, muon and tau.

Electrons take up space

Muons unstable

$$\mu^- \rightarrow \overline{\nu}_\mu + e^- + \overline{\nu}_e$$

(cosmic rays)

Taus very unstable

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Quarks give most of mass

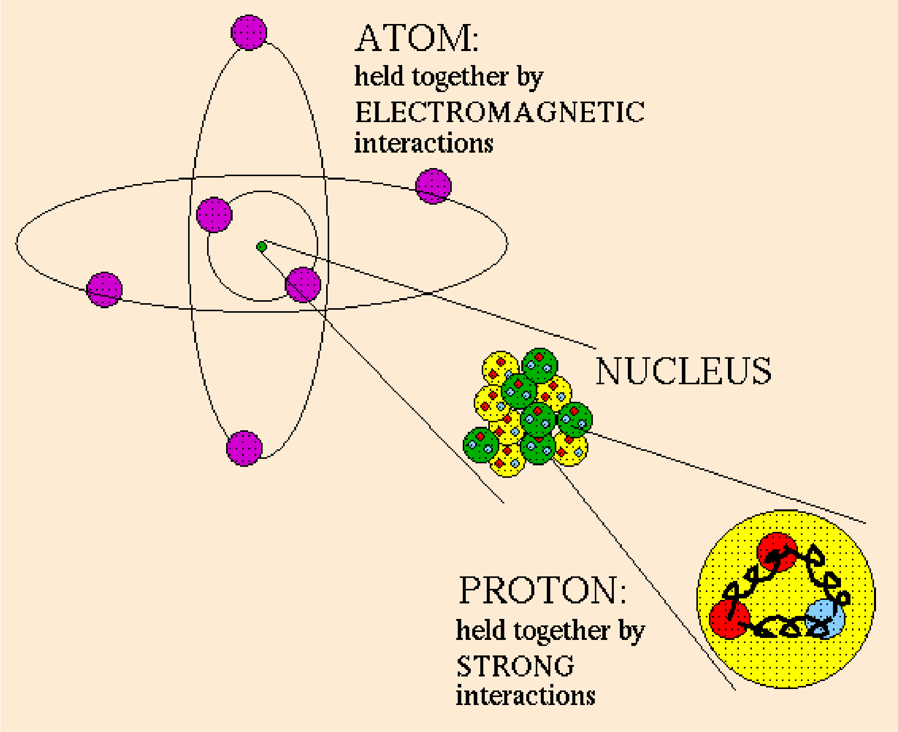
Protons: uud

Neutrons: ddu

Exotic quarks: rare and unstable

1. The structure of matter (cont.)

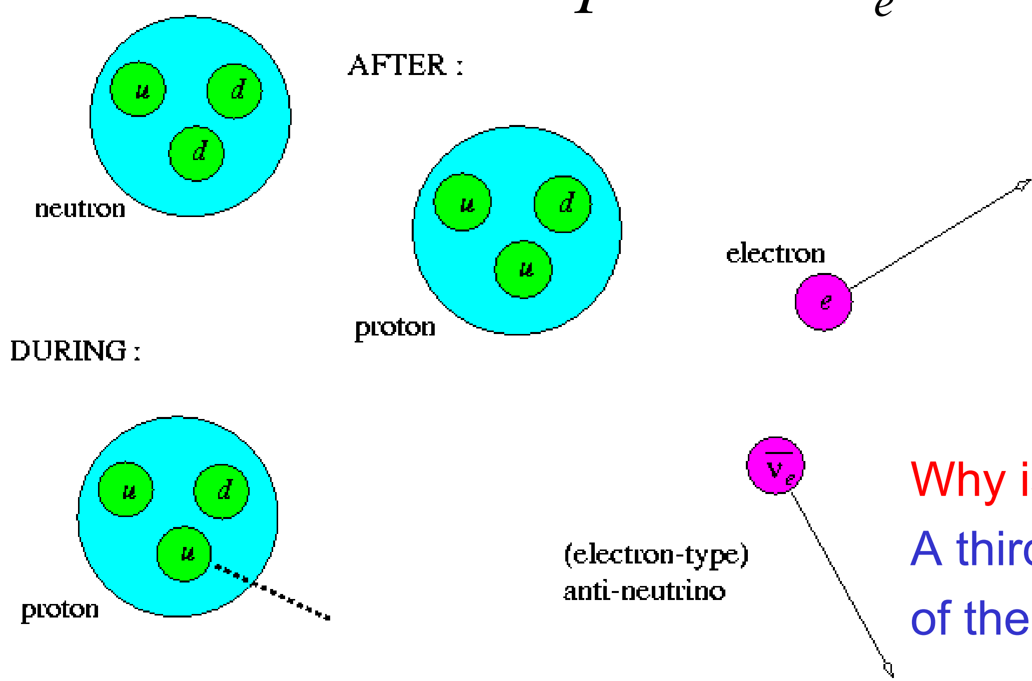
- Forces:
  - Gravity: very weak, long interaction, mediated by graviton (never observed!).
  - Electromagnetic: keeps atoms together, mediated by photon
  - Strong: keeps nuclei and nucleons (ie. protons, neutrons) together, mediated by gluons. Very short range interaction
  - Weak: responsible for some radioactive decays (ie. beta decay), mediated by W^+, W^- and Z^0 massive gauge bosons. Relatively short range and weak due to mass of the bosons.

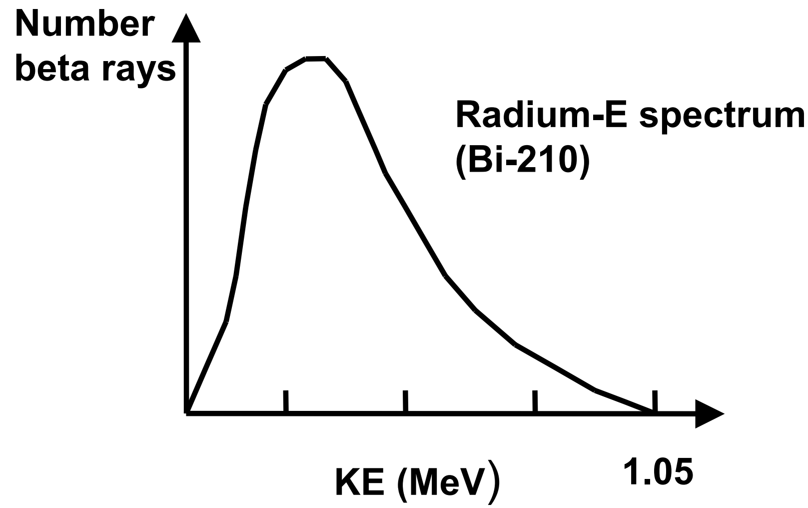


2. Neutrinos:

- Neutrinos:
  - Originally suggested by Pauli in 1930 as a “desperate remedy to overcome “law of conservation of energy” in beta decay:

$$n \rightarrow p + e^{-} + \overline{\nu}_e$$





Why is the electron spectrum continuous?

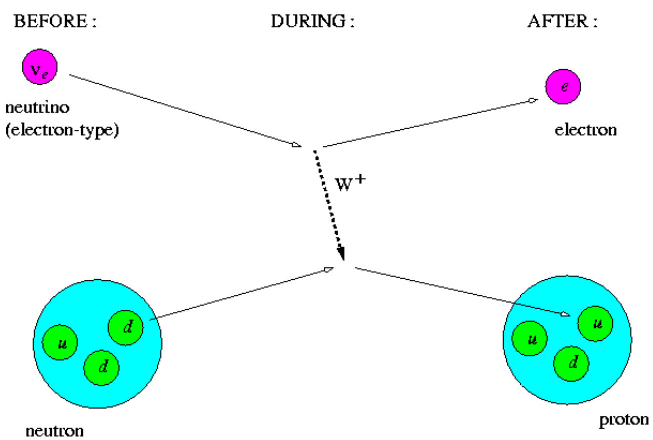
A third particle (neutrino) is taking away part of the energy

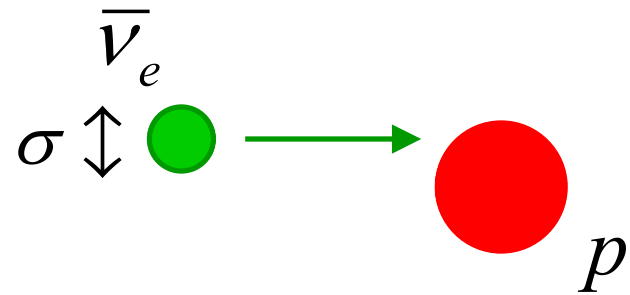
  - The neutrino was originally postulated as a massless, chargeless and very weakly interacting particle: practically indetectable!

2.1 Neutrino interactions

- Neutrino interactions:
  - One of the ways neutrinos interact is through inverse beta decay:

$$\nu_e + n \rightarrow p + e^- \quad \text{or} \quad \overline{\nu}_e + p \rightarrow n + e^+$$





  - Cross-section σ (average area of neutrino in collision) is very small: on average a neutrino would travel 1600 light-years of water before interacting!

$$\sigma \approx 10^{-44}\ cm^2$$

Mean free path: $\lambda = \dfrac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600$ light-years

$$n = \frac{num.\ free\ protons}{volume} \approx 2\frac{N_A}{A}\rho$$

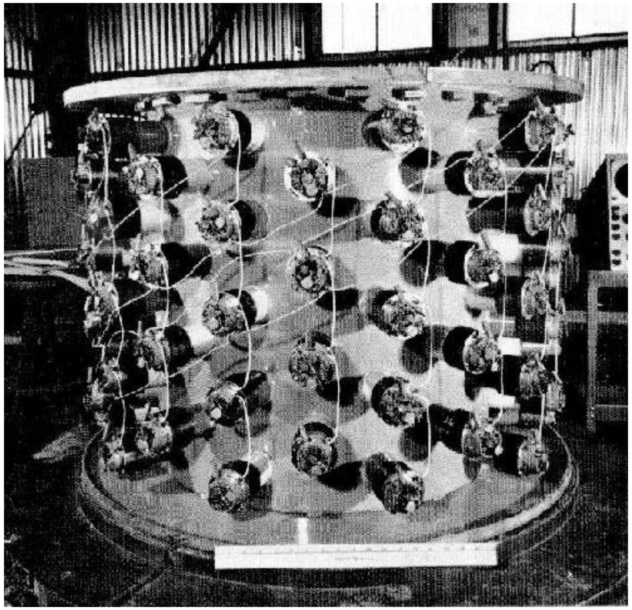
In water: $n = \dfrac{2 \times 6 \times 10^{23}}{18} = 6.7 \times 10^{22}\ cm^{-3}$

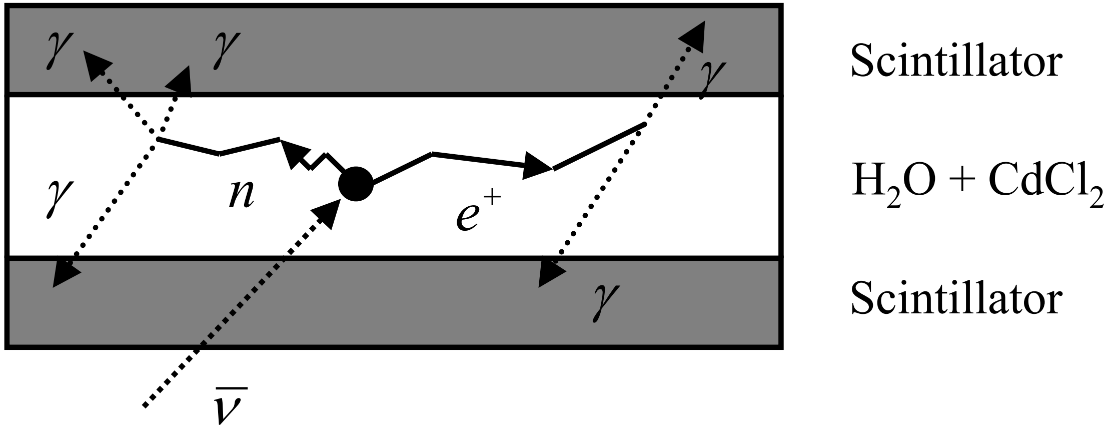
2.2 Neutrino discovery

- Reines and Cowan observed neutrinos for the first time in 1953 (Nobel prize for Reines in 1995)
- They used 400 l of a mixture of water and cadmium chloride (Cd)
- An antineutrino from a nuclear reactor (6 x10^{20} s^{-1}) very rarely interacted with the protons in the target (2.8 hr $^{-1}$):

$$\bar{\nu}_e + p \rightarrow n + e^+$$

  - The positron (e^+) produces two photons, followed about 20 ms later by the neutron interacting with a Cd nucleus that produced another spray of photons





2.2 Neutrino questions

- Neutrinos are all around us:
  - Produced by nuclear reactions in radioactive rocks (trace uranium thorium in granite, etc.), in the sun (solar neutrinos) and from cosmic rays hitting the atmosphere (atmospheric neutrinos).
  - Very difficult to detect because they are so weakly interacting.
  - Produced in copious quantities inside nuclear reactors.
  - Generated by high energy accelerators
- Two main problems:
  - Solar neutrino problem: nuclear reactions in the sun produce electron neutrinos ν_e (energies up to 14 MeV). The number detected on earth by experiments is between 30%-50% of what is expected.
  - Atmospheric neutrino problem: high energy particles (cosmic rays) hitting the upper part of the atmosphere. There should be twice as many muon neutrinos ν_μ as electron neutrinos ν_e (energies up to 10 GeV). Experiments detect approximately equal numbers.
- Both can be resolved through neutrino oscillations

2.3 Neutrino oscillations

- If neutrinos have mass, theoretically, a neutrino of one species could change into another species:
  - For example: a muon neutrino changes into a tau neutrino

$$\nu_\mu \rightarrow \nu_\tau$$

  - Probability that a ν_μ of energy E converts to a ν_τ after travelling a distance L is:

$$\Pr(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{\mu\tau})\sin^2\left(\frac{1.27\left(m_{\nu_\tau}{}^2 - m_{\nu_\mu}{}^2\right)L}{E}\right)$$

Notice that the probability of oscillations is zero if the mass of the neutrinos are zero!

L=length of neutrino path (in m)

E=energy neutrino (in MeV)

m_{ν_μ}= mass of ν_μ (in eV)

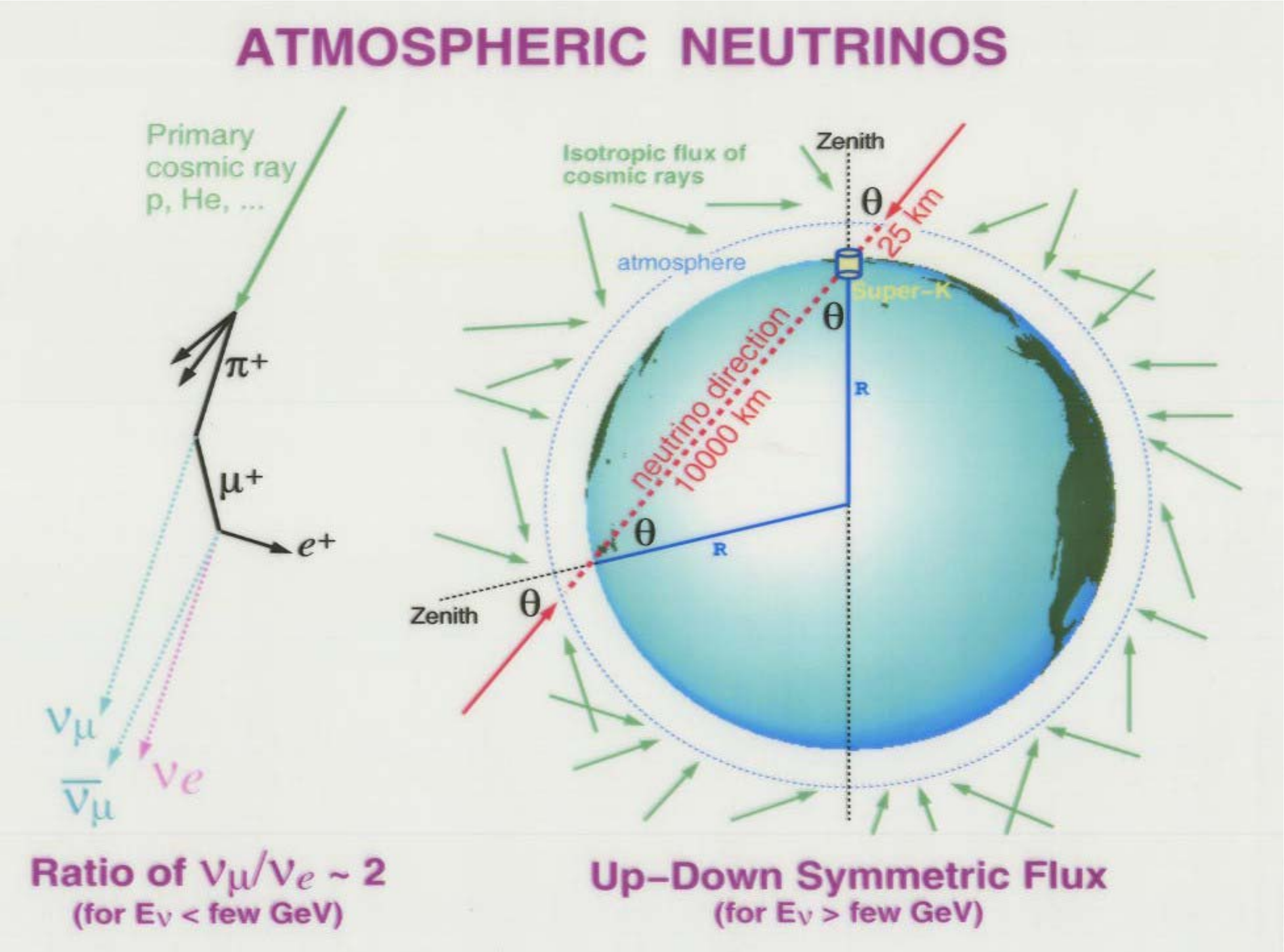
m_{ν_τ}= mass of ν_τ (in eV)

$\theta_{\mu\tau}$=mixing angle between two neutrinos

(eV= electronVolt=energy of one electron accelerated by 1 Volt=1.6×10^{-19} J)

3. Atmospheric Neutrinos

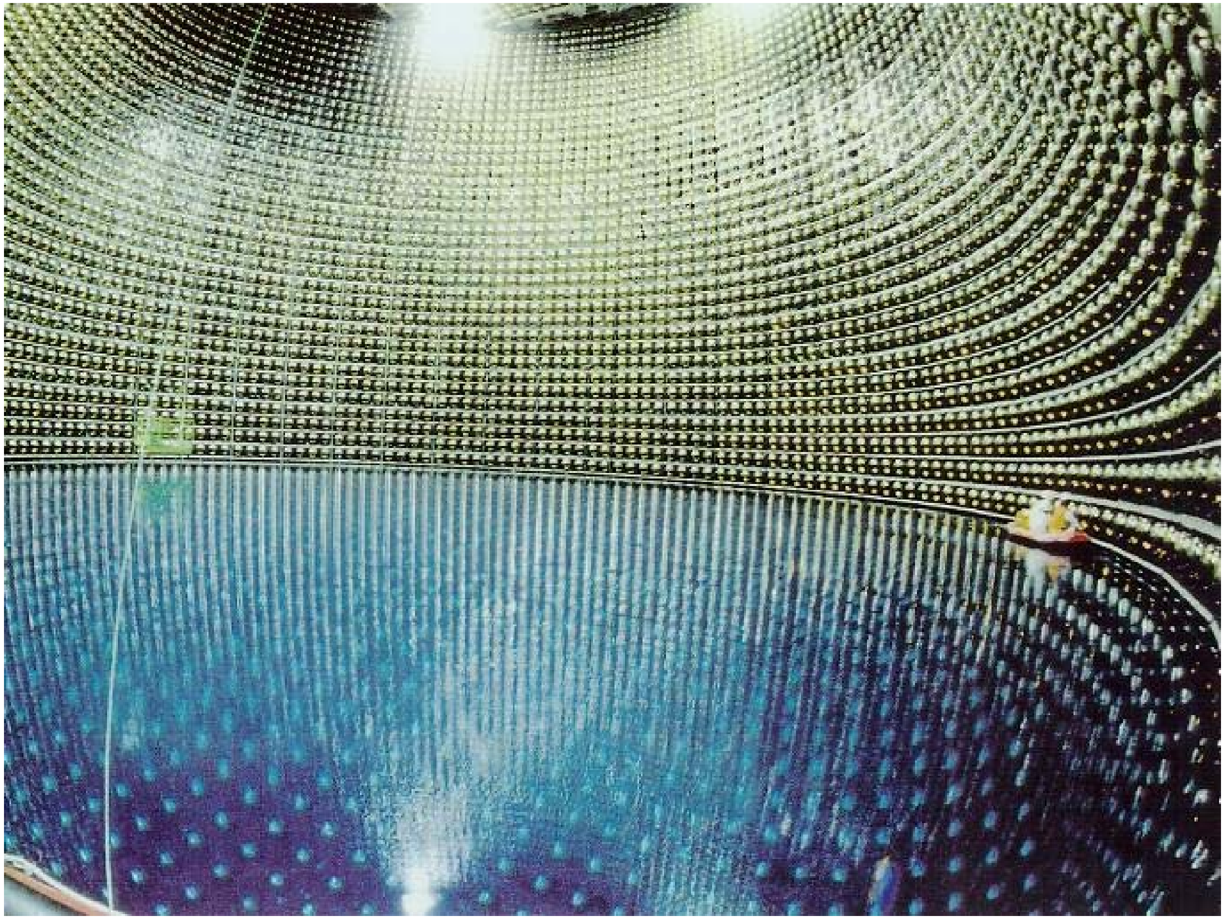
- Cosmic rays provide an abundant source of neutrinos.
- Protons hit upper part of atmosphere producing cascade of particles including (on average) 2 muon neutrinos for each electron neutrino produced in an interaction



3.1 Super-Kamiokande experiment

- Kamiokande experiment: started 1987, 5000 tons water, 1000 photomultipliers
- Super-kamiokande experiment: started 1997

  50,000 tons of water, surrounded by 11,000 phototubes to detect flashes of light in the water.



Super-Kamiokande experiment is underground Inside a mine in Japan to shield it from the very large number of cosmic rays.

3.1 Super-Kamiokande experiment

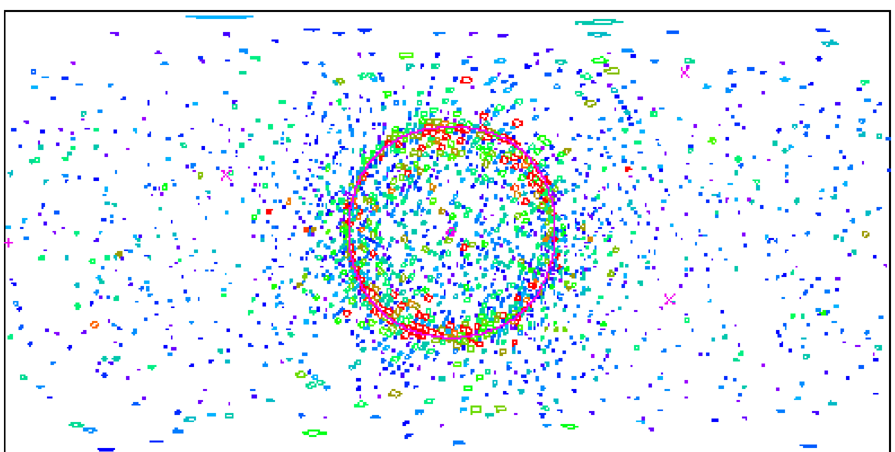
- Super-Kamiokande detects faint flashes of Cherenkov light inside huge tank of 50,000 tons of water.
- Electron neutrinos make a recoil electron and muon neutrinos make a recoil muon.

$$\nu_e + N \rightarrow e^- + X$$

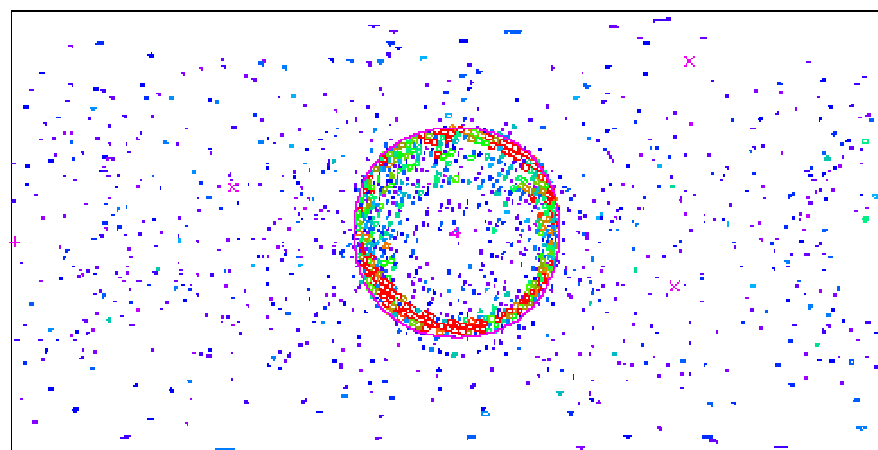
$$\nu_\mu + N \rightarrow \mu^- + X$$

- Rings of Cherenkov light are formed from the electron or the muon. The detector can distinguish between electrons (fuzzy rings) and muons (clean edge on ring).

Electron-like

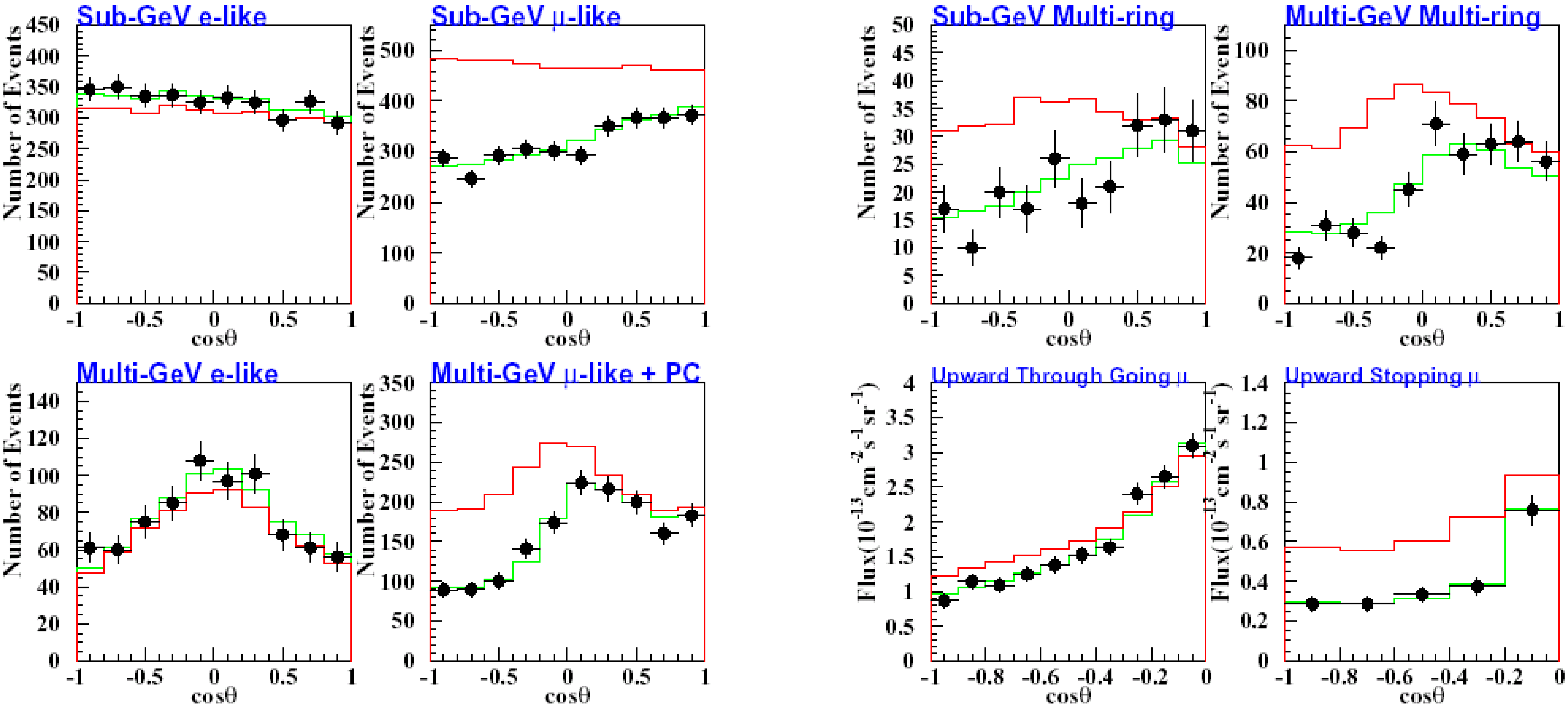


Muon-like



3.2 Discovery of neutrino mass

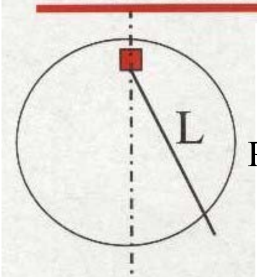
- Results from Super-Kamiokande:
  - There are less muon neutrinos than expected. The number of muon neutrinos disappearing depends on the angle of the neutrino (ie. It depends on whether the neutrino was produced in the atmosphere above or on the other side of the earth). First evidence for neutrino oscillations in 1998 !!!!



3.2 Discovery of neutrino mass

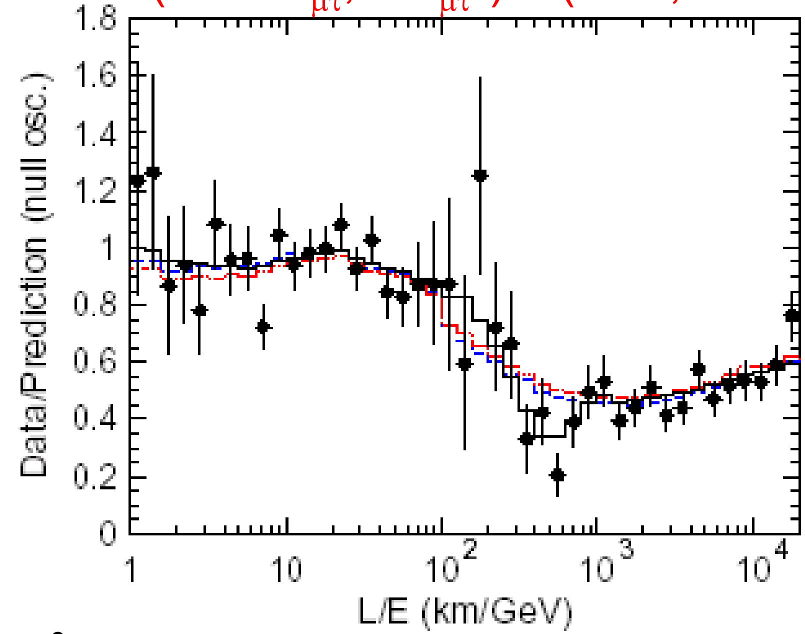
- As the distance from production increases then more muon neutrinos disappear.

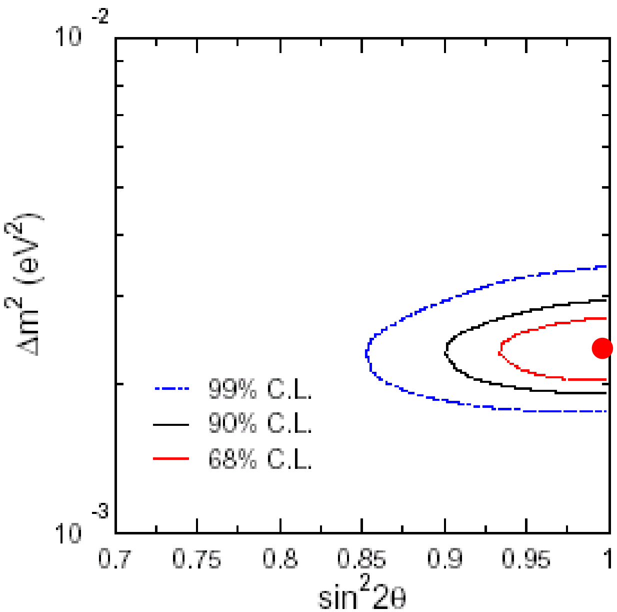
Bin data as a function of L/E_ν



$$\Pr(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{\mu\tau})\sin^2\left(\frac{1.27\Delta m_{\nu_\tau\nu_\mu}{}^2 L}{E}\right)$$

Best fit: $(\sin^2 2\theta_{\mu\tau}, \Delta m_{\mu\tau}{}^2) = (1.00, 2.4\times10^{-3})$





$$\theta_{\mu\tau} = 45^\circ \Rightarrow \sin^2(2\theta_{\mu\tau}) = 1.00$$

$$\Delta m_{\nu_\tau\nu_\mu}{}^2 = 2.4^{+0.6}_{-0.5}\times10^{-3}\ eV^2 \Rightarrow \Delta m_{\nu_\tau\nu_\mu} = 0.049 \pm 0.006\ eV$$

A minimum is observed at: L/E ~ 500 km/GeV

$$L/E = 500\ km/GeV \Rightarrow \Pr(\nu_\mu \to \nu_\tau) = \sin^2(1.52\,rad) = \sin^2(87^\circ) = 1.0$$

All ν_μ convert to ν_τ !

3.2 Discovery of neutrino mass

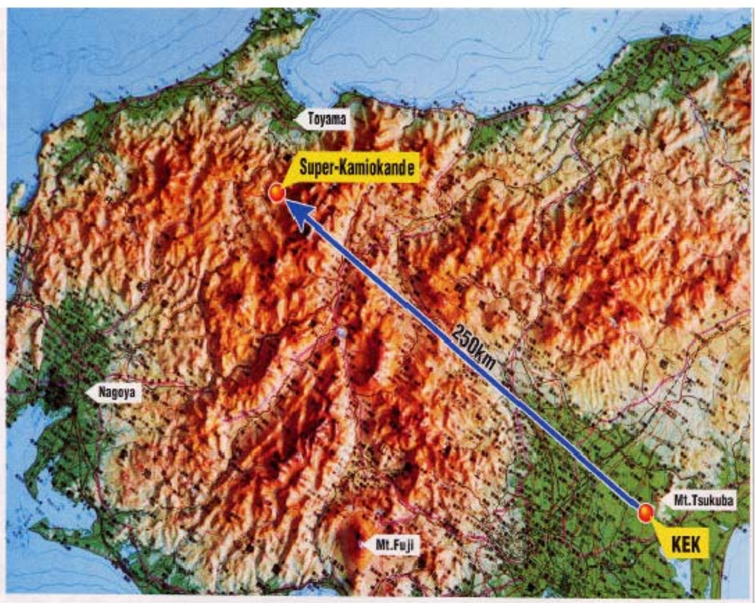
- Consequences of discovery:
  - Neutrino oscillations responsible for atmospheric muon neutrino deficit.
  - Since electron neutrino spectrum well predicted, it must be muon neutrinos ν_μ changing into tau neutrinos ν_τ .
  - Since $\left(m_{\nu_\tau}{}^2 - m_{\nu_\mu}{}^2\right) = 2.4 \times 10^{-3}\ eV^2$ then neutrinos have mass!!
  - Mass of the neutrinos have to be greater than 0.049+-0.006 eV.

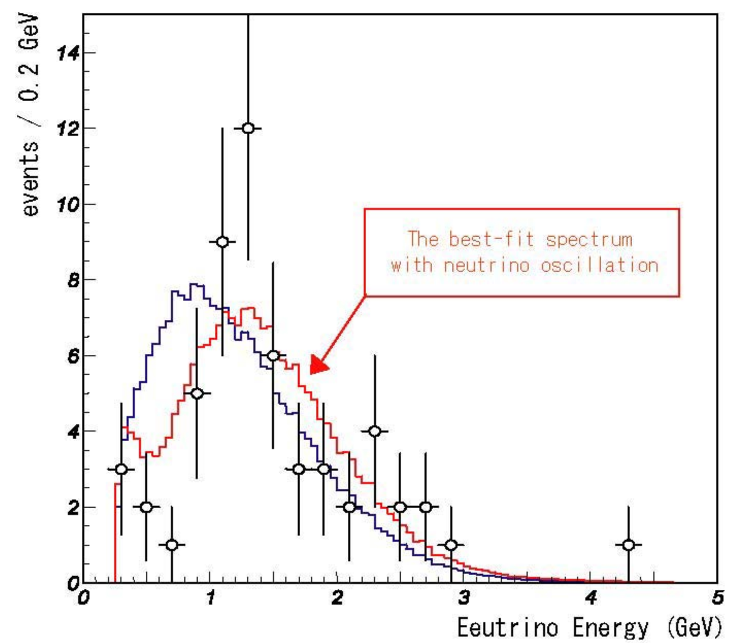
    If either the ν_μ or ν_τ is much smaller than the other, then m_ν~0.05 eV.

    Both ν_μ or ν_τ could have a mass much larger than m_ν~0.05 eV as long as the difference of the mass squared is 2.4×10^{-3} eV^2.
- Since there were so many neutrinos produced soon after the big-bang, if they have a mass, it could provide a large portion of the missing mass of the universe (up to 20%).

3.3 Long-baseline experiments

- Long-baseline experiments with accelerators will verify that oscillations are really taking place in Super-Kamiokande.
  - K2K (from the KEK accelerator in Japan to Super-Kamiokande): 250 km baseline of neutrinos. So far they observe 108 ν_μ events when they expected 150.9 (+11.6,-10.0) events, consistent with ~3×10^{-3} eV^2 mass-squared difference.





  - MINOS: neutrino beam from Fermilab in Chicago to a mine in Minnesotta (750 km), will start taking data in 2005. Another beam from CERN to Gran Sasso (CNGS) laboratory in Italy (also 750 km) to start in 2006.