Previous Lecture

- Standard Solar Model
- SNO
  - Detected processes (CC, NC, ES)
  - Flux measurements

Lecture Content

- Approx. lecture content
  1. PP intro
  2. PP intro.
  3. ν props 1: strong/e.m./weak, no. neutrino generations
  4. ν props 2: lepton no., ν existence
     - Examples of decay/production
  5. Neutrino mass
     - Fermi-Kurie plot
     - Phase space kinematics/4-momentum
  6. Parity and CP violation… (why so important in lepton sector?)
     - Wu et al., ^{60}Co experiment
  7. Detection & observation
     - Liquid, solid, bubble chamber
     - "Direct" methods (DONUT)
  8. Atmospheric neutrinos
     - Cerenkov detectors
     - SuperKamiokande experiment
  9. Atmopsheric neutrino data and oscillations
     - Interpretation of atmospheric ν data
     - Two-flavour neutrino oscillation formalism
  10. Solar neutrinos and SSM
      - SNO experiment and data/SSM predictions
  11. Subject Outlook
      - NDBD (NEMO, etc.)
      - Subject outlook (JPARC, MICE, Neutrino Factory, SK, SNO, KAMLAND, CHOOZ MINOS, miniBOONE, JPARC, νF,

Today

- SNO
  - Detected processes (CC, NC, ES)
  - Flux measurements
- Neutrinoless Double Beta Decay
  - Dirac vs. Majorana neutrinos
  - See Zuber article on web page
    - ⇒ Acta Physica Polonica B Vol. 37, No. 7, July 2006, page 1905
  - See also Sutton "Spaceship Neutrino", pp. 64-70
- Long baseline experiments
- Selected slides from
  - ICFA seminar, SLAC, Oct.2008
- Please look through additional references on course web page:
  - https://www.ep.ph.bham.ac.uk/twiki/bin/view/General/Y2Neutrinos

Neutrinolessdouble beta decay

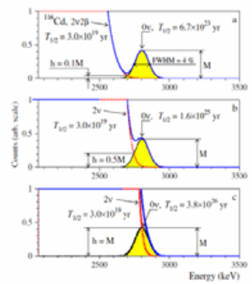


Figure 2. Example of the discovery potential of the 2β decay studies. The 2ν distribution of ^{116}Cd (with $T^{2\nu}_{1/2} = 3\times10^{19}$ years) overlaps the 0ν peaks with half-life corresponding to (a) 6.7×10^{23} years; (b) 1.6×10^{25} years; and (c) 3.8×10^{26} years. Correspondingly, the 0ν peak with the amplitude M (the energy resolution at 2.8 MeV is FWHM = 4%) and the 2ν spectrum meet at the relative height h/M for (a) 0.1; (b) 0.5; (c) 1.

From F.T.Avignone, G.S.King, Yu.G.Zdesenko, *New Journal of Physics* 7 (2005) 6

- Potentially large background from 2νBD, see figure
- Observation would show
  - ν is its own antiparticle
  - ν has non-zero mass

2NBD/NDBD

6 EPI2006 PRINTED ON OCTOBER 4, 2006

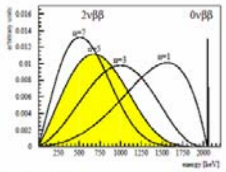


Fig. 3. Schematic drawing of the sum energy spectrum of electrons in double beta decay, here in case of ^{76}Ge. The $2\nu\beta\beta$-decay shows a continous spectrum (yellow), while $0\nu\beta\beta$-decay is a peak at the Q-value of the transition. The additional curves shown correspond to various majoron emitting modes not discussed here.

Transition	Q-value (keV)	nat. ab. (%)
$^{48}_{20}Ca \rightarrow ^{48}_{22}Ti$	4271	0.187
$^{76}_{32}Ge \rightarrow ^{76}_{34}Se$	2039	7.8
$^{82}_{34}Se \rightarrow ^{82}_{36}Kr$	2995	9.2
$^{96}_{40}Zr \rightarrow ^{96}_{42}Mo$	3350	2.8
$^{100}_{42}Mo \rightarrow ^{100}_{44}Ru$	3034	9.6
$^{110}_{46}Pd \rightarrow ^{110}_{48}Cd$	2013	11.8
$^{116}_{48}Cd \rightarrow ^{116}_{50}Sn$	2809	7.5
$^{124}_{50}Sn \rightarrow ^{124}_{52}Te$	2288	5.64
$^{130}_{52}Te \rightarrow ^{130}_{54}Xe$	2530	34.5
$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba$	2479	8.9
$^{150}_{60}Nd \rightarrow ^{150}_{62}Sm$	3367	5.6

Table 1. Compilation of $\beta^-\beta^-$-emitters with a Q-value of at least 2 MeV. Shown are the transition energies Q and the natural abundances.

From K.Zuber
arXiv:nucl-ex/0610007, Oct 2006
(same as **Acta Physica Polonica B Vol. 37, No. 7, July 2006, page 1905)**

NEMO/Super-NEMO

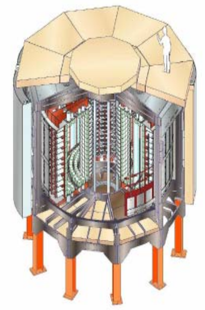
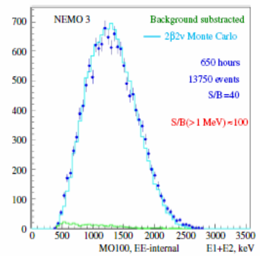


Figure 17. An artist's conception of the NEMO detector, showing a cartoon of a normal size person to demonstrate its dimensions.

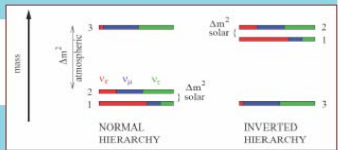


ure 19. An energy spectrum of the sum energy of the two electrons from the -neutrino double-beta decay of ^{100}Mo measured in the NEMO detector.

From F.T.Avignone, G.S.King, Yu.G.Zdesenko, *New Journal of Physics* 7 (2005) 6

Neutrino oscillations:
What we know and what we don't know

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3}\\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3}\\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



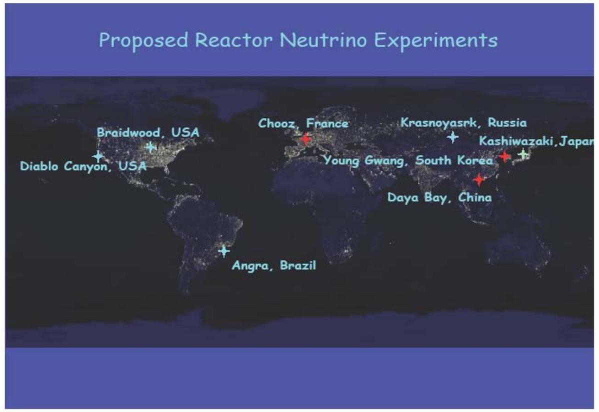
Atmospheric | CP phase & θ_{13} | Solar | Majorana phase

$$V = \begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}\\ 0 & e^{-i\delta} & 0\\ -s_{13} & 0 & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix} e^{i\rho} & 0 & 0\\ 0 & e^{i\sigma} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- Unknown parameters in neutrino oscillation:
  - **θ_{13}, mass hierarchy, CP phase δ** + Majorana phase

[From Yifang Wang, ICFA seminar, Oct. 2008]

Large number of proposed experiments



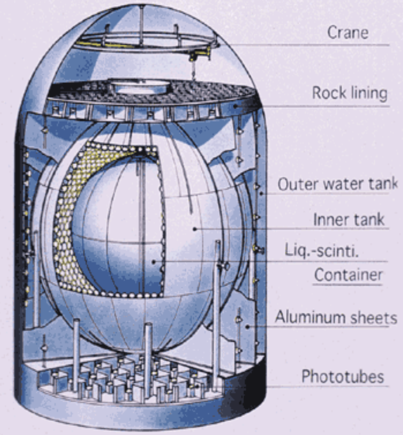
[From Yifang Wang, ICFA seminar, Oct. 2008]

KAMLAND detector

- Demonstration of oscillations with ν created in lab.
  - controlled conditions

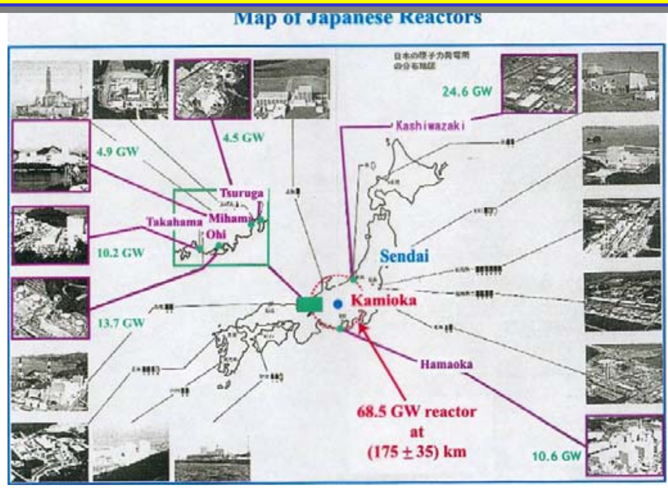
$$P = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{E_\nu}L\right)$$

- Difficult if Δm^2 small
- Need low E_ν, high Φ_ν
- Favoured parameters suggest use L~100km
- Create low E ν in nuclear reactors

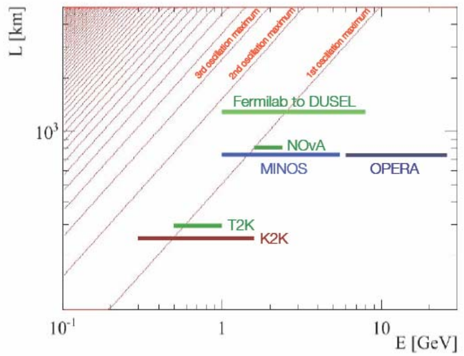


1 kt

KAMLAND



Comparison of L/E: existing/future expts.

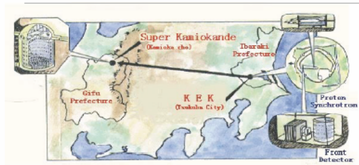


Long baseline experiments $P = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L[\text{km}]}{E[\text{GeV}]}\right)$

[From, Mark Messier, ICFA seminar, Oct. 2008]

K2K

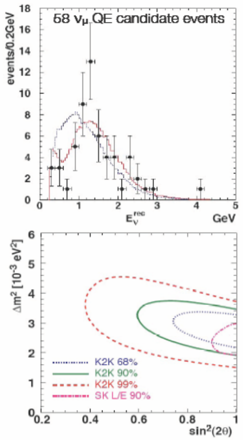
K2K Experiment (1999-2004)



- L = 250 km
- E = 0.3 - 1.8 GeV
- $1\text{x}10^{20}$ POT delivered

	K2K-I			K2K-II		
	data	expected w/o osc.	expected w/ osc.	data	expected w/o osc.	expected w/ osc.
Fully contained	55	80.8	54.8	57	77.3	52.4
1-ring	33	51.0	31.1	34	49.7	30.5
μ-like	30	47.1	27.7	28	45.2	26.7
e-like	3	3.9	3.4	6	4.5	3.8
multi-ring	22	29.8	23.7	23	27.6	21.9

$\Delta m^2 = 2.8^{+0.5}_{-0.6} \times 10^{-3}$ eV^2 [68% C.L.]



[From, Mark Messier, ICFA seminar, Oct. 2008]

T2K

T2K: Tokai-to-Kamioka

Tokai-to-Kamioka neutrino oscillation experiment

- to precisely measure the ν_μ disappearance, i.e. θ_{23} and Δm^2_{23} ($\sim\Delta m^2_{13}$)
- to intensively search for $\nu_\mu \rightarrow \nu_e$ appearance, i.e. non-zero θ_{13}

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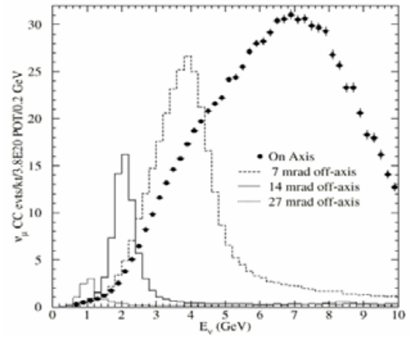
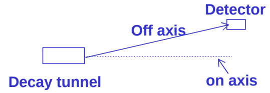
[From, Mark Messier, ICFA seminar, Oct. 2008]

superbeams/'Off-axis' expts.



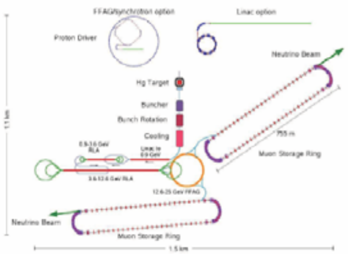


Gives smaller energy spread and can adjust the energy.

Neutrino Factory: >2020?

Neutrino Factory

- NF International Scoping Study (ISS-NF, 2005-2008) is finished, reports published (arXive → JINST):
  - Physics
  - Accelerator
  - Detector



Shiltz

[From, Ed Kearns, ICFA seminar, Oct. 2008]