$\sin^2\theta_{13}$ VALUE LIMIT IN DOUBLE CHOOZ EXPERIMENT

Pi-Jung Chang

Outline

- Discovery neutrino
- Neutrino oscillation
- Double Chooz experiment
  - Detector structure
  - Neutrino source
  - Backgrounds
- Systemic uncertainties
  - Uncertainties in Double Chooz experiment
  - Sensitivity models
- Recent work
  - Energy scale
  - Environmental monitoring system
  - Final fitting process
- Conclusion

DISCOVERY NEUTRINO

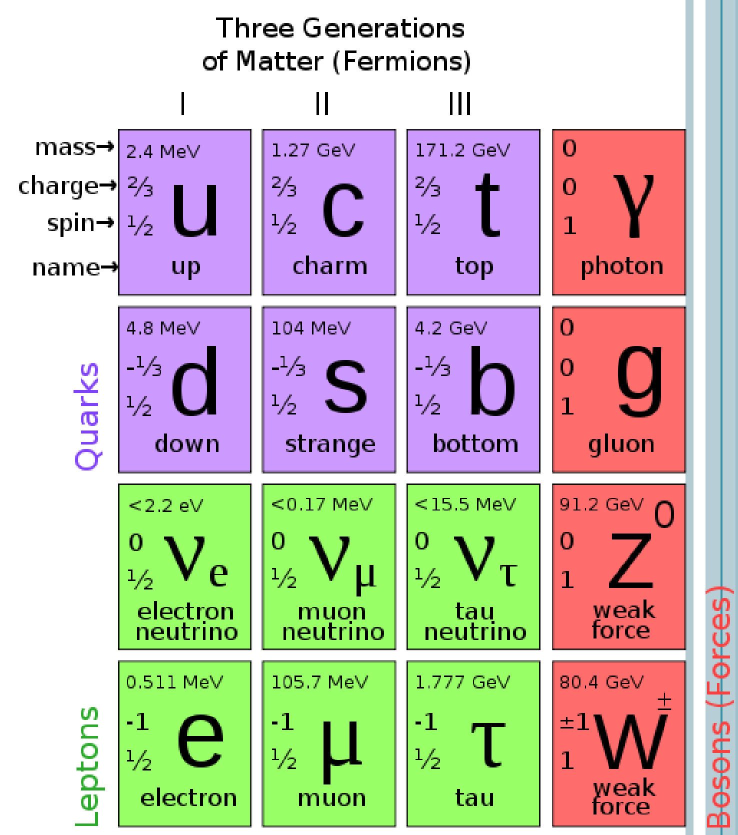
- The neutrino was first postulated theoretically.
  - Pauli ->Beta decay in 1930

$$M(A,Z) -> D(A,Z+1) + e^{-} + \bar{\nu}_e$$

- prove by Cowan and Reines(1956)
  - Electron anti-neutrino from nuclear reactors

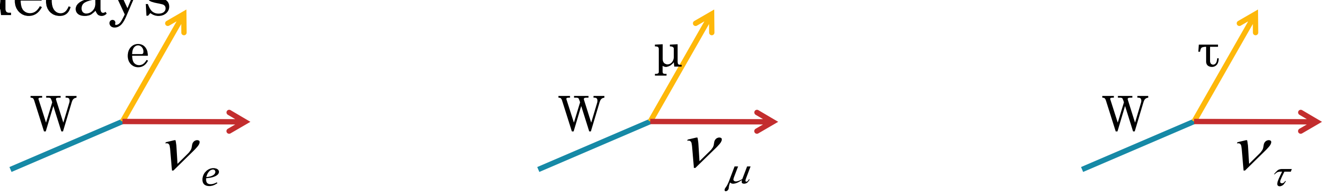
$$\bar{\nu}_e + p -> e^{+} + n$$

- 1962 muon neutrinos (Danby et al 1962)
- 1975 tau lepton-> tau neutrinos(Kodama et al 2001)

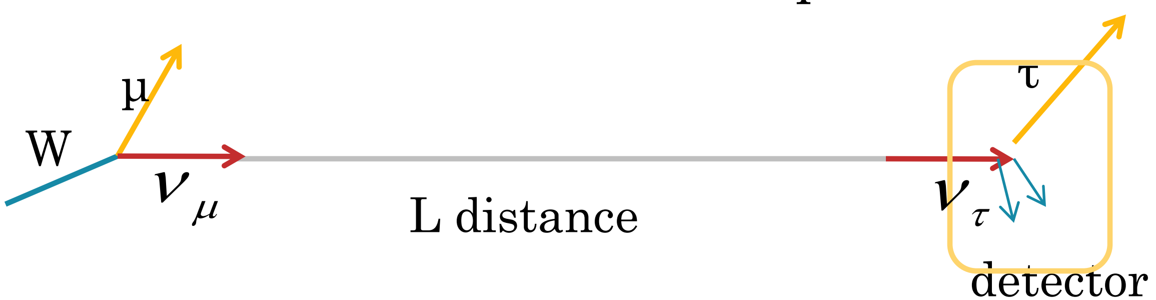


Neutrino Oscillation

- Three known flavor neutrinos from W boson decays

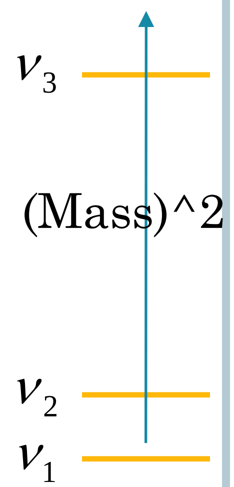


- Neutrino Flavor Change
  - If neutrino has masses and leptons mix.



"Neutrino Phenomenology Facts, and Question" Boris Kayser 2009 neutrino summer school

Neutrino Oscillation



- Linear superpositions of mass eigenstates

$$|\nu_l\rangle = \sum_i U_{l,i}\,|\nu_i\rangle \qquad \text{l=e,τ,μ ; i=3,4....}$$

Weak eigenstates $|\nu_l\rangle$, mass eigenstates $|\nu_i\rangle$, leptonic mixing matrix $U_{l,i}$, at least i=3 mass eigenstates.

$$|\nu_i(t)\rangle = e^{-i(E_i t - pL)}|\nu_i(0)\rangle \cong e^{-i(m_i^2/2E)L}|\nu_i(0)\rangle$$

$$|\nu_l(L)\rangle \cong \sum_i U_{l,i} e^{-i(m_i^2/2E)L}|\nu_i(0)\rangle \cong \sum_l \sum_i U_{l,i} e^{-i(m_i^2/2E)L} U^*_{l',i}|\nu_{l'}(0)\rangle$$

- Probability

$$P(\overset{(-)}{\nu}_l(L) \to \overset{(-)}{\nu}_{l'}) = \left|\sum_i U_{l,i} U^*_{l',i} e^{-i\left(m_i^2/2E\right)L}\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j=1}^{3}\mathrm{Re}\left(K_{\alpha\beta,ij}\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \underset{(-)}{+} 4\sum_{i>j=1}^{3}\mathrm{Im}\left(K_{\alpha\beta,ij}\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)\cos\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$K_{\alpha\beta,ij} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}$$

“Reactor-based Neutrino Oscillation Experiments“ Carlo Bemporad et al.

Neutrino Oscillation

- The Mixing Matrix U

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric Cross-Mixing Solar

$$c_{ij} \equiv \cos\theta_{ij}, s_{ij} \equiv \sin\theta_{ij}, \theta_{12} \sim \theta_{sol}, \theta_{23} \sim \theta_{atm}.$$

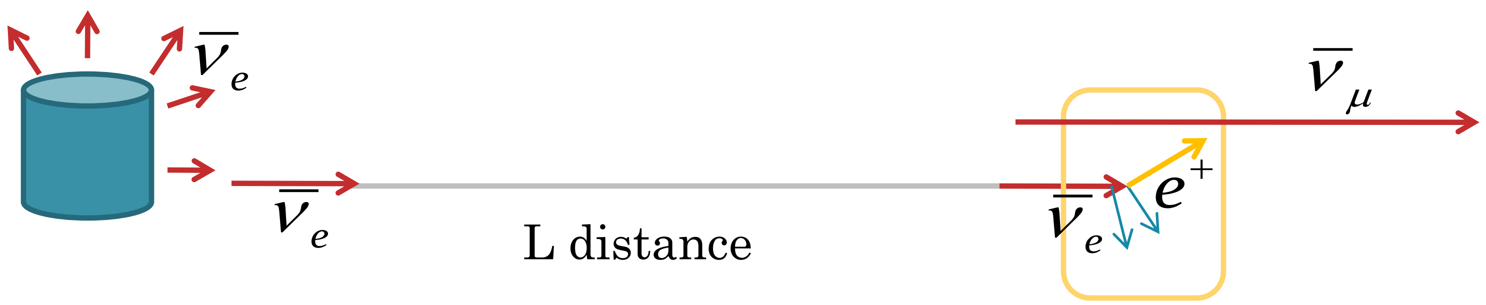
δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$ CP violation

- CP violation disappears : $\sin\theta_{13} \to 0$

“Neutrino Phenomenology Facts, and Question” Boris Kayser 2009 neutrino summer school

REACTOR NEUTRINO EXPERIMENTS PROPERTIES

- $\bar{\nu}_e$ -> beta decay of the neutron-rich fission fragment
- Energy is low(few MeV)-> only $\bar{\nu}_e$ disappearance
- Flux->large solid angle and low signal rates
- There is no beam alignment problem



"Reactor-based Neutrino Oscillation Experiment" Carlo Bemporad et al..
"Neutrino Physics" Kai Zuber.

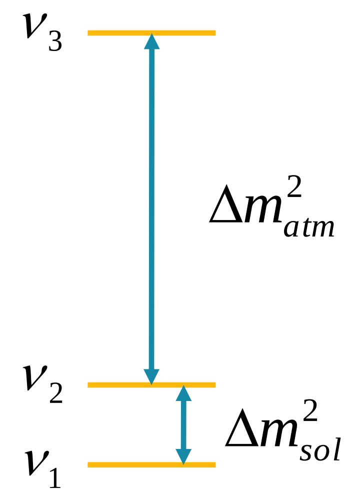
Reactor experiments

- Reactor neutrino experiment

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2 2\theta_{13}\sin^2\theta_{12}\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

$$-\sin^2 2\theta_{13}\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

$$\cong 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$



  - Doesn’t depend on the δ-CP phase
  - Short baseline experiment
  - Experimental data

$$\Delta m^2_{atm} \cong 2.4\times 10^{-3} eV^2, \Delta m^2_{sol} \cong 7.6\times 10^{-5} eV^2$$

$$\sin^2 2\theta_{23} \cong 1, \sin^2 2\theta_{12} \cong 0.8, \sin^2 2\theta_{13} < 0.1$$ Chooz data

“Fundamentals of Neutrino Physics and Astrophysics” Carlo Giunti and Chung W. Kim

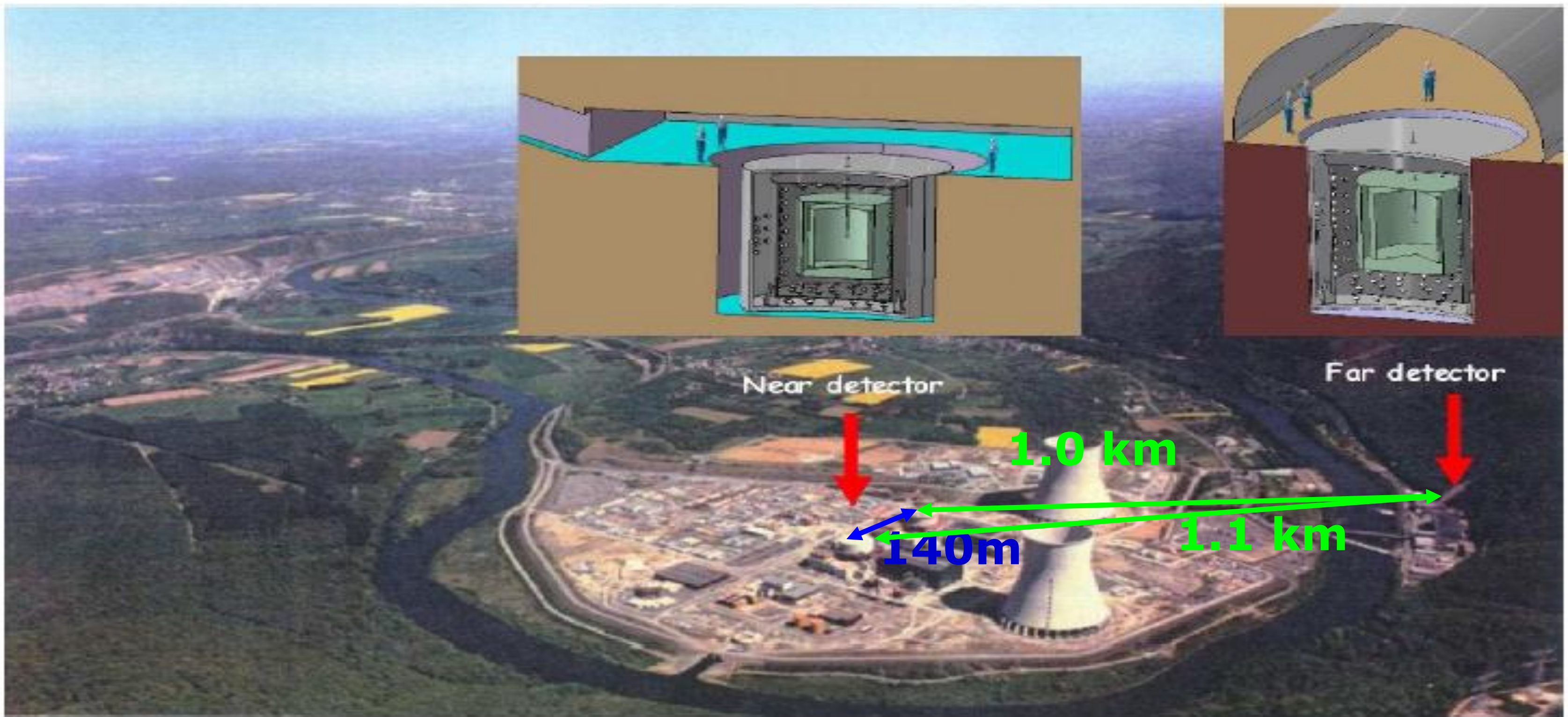
LOCATION


North Sea
United Kingdom
Leeds
Bristol
London
Amsterdam
Nederland
Belgie
Luxembourg
Reims
Paris
France
Le Havre
Rennes
Nantes
Bordeaux
Toulouse
Lyon
Marseille
Toulon
Danmark
København
Hamburg
Bremen
Hannover
Berlin
Essen
Deutschland
Frankfurt am Main
Mannheim
Stuttgart
München
Nürnberg
Dresden
Leipzig
Magdeburg
Polska
Warszawa
Łódź
Kraków
Wrocław
Poznań
Česká Republika
Brno
Wien
Österreich
Schweiz
Suisse
Svizzera
Milano
Torino
Genova
Bologna
Venezia
Italia
Roma
Slovenija
Zagreb
Hrvatska
Budapest
Magyarország
Slovensko
Beograd
Bosna i Hercegovina
Sofia
Lietuva
Kaunas

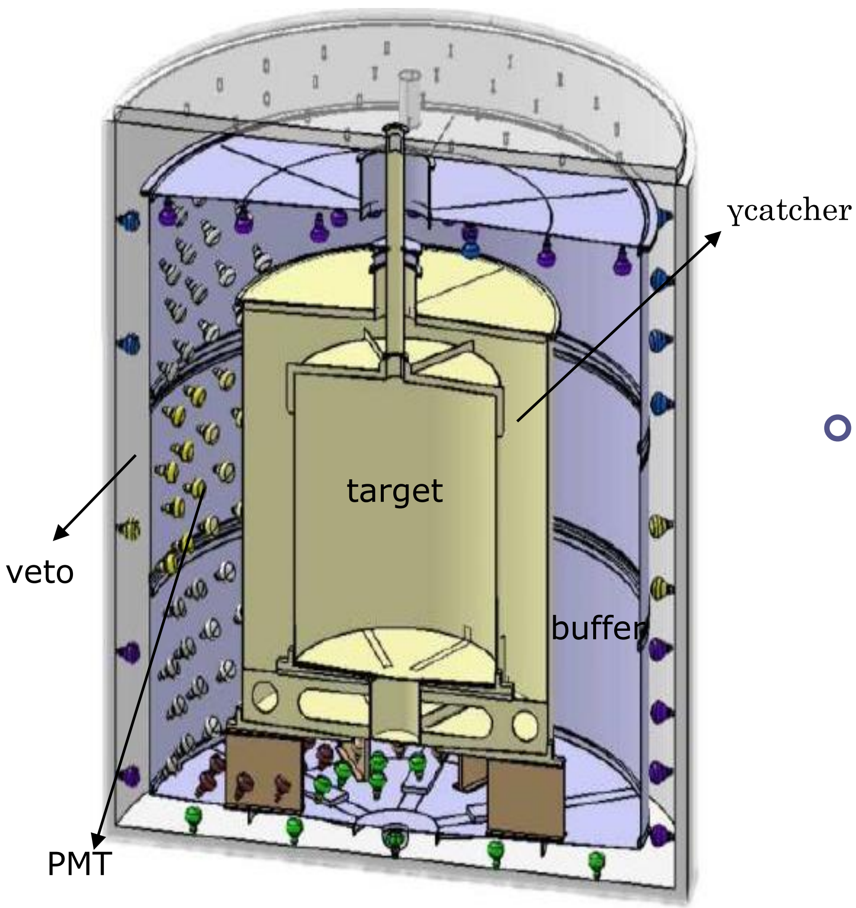
Introduction Double CHOOZ

- Antineutrino flux ← the two nuclear cores of the Chooz power plant results from β− decay of the fission products of four main isotopes ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U.

$$\overline{\nu_e} + p \rightarrow e^{+} + n$$



Detector structure

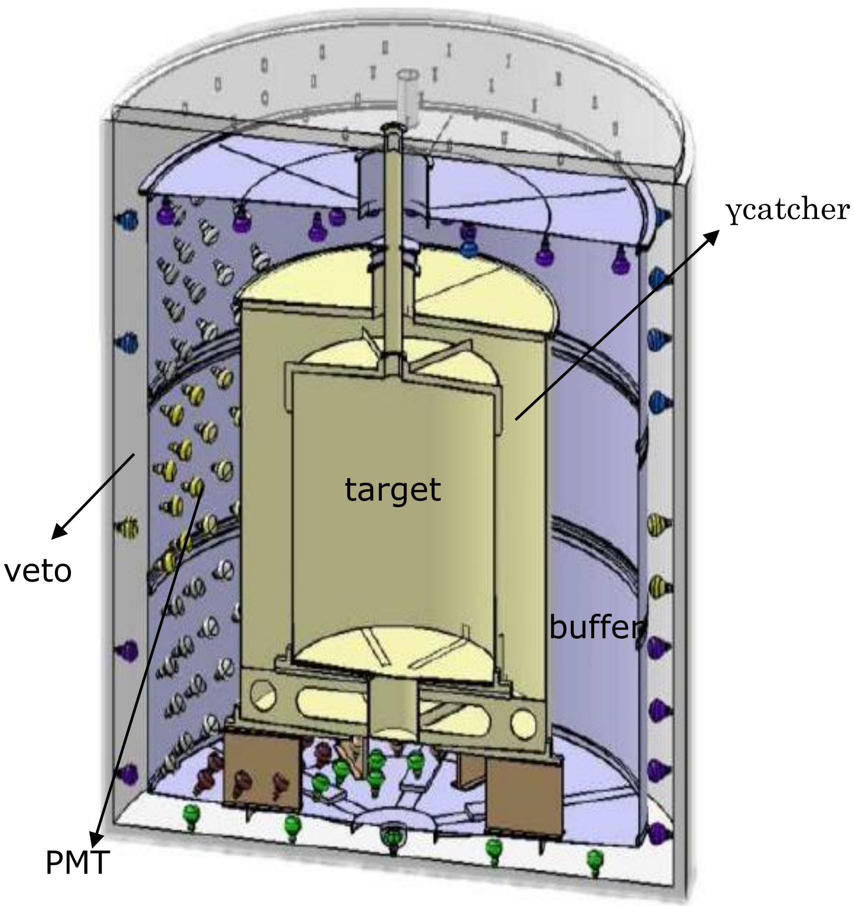


- Scintillator (target):
  - Proton -> 20% PXE($C_{16}H_{18}$) , 80% of dodecane($C_{12}H_{26}$), small amount gadolinium
  - Neutron capture -> small amount gadolinium

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

- Γ catcher:
  - the same optical properties as target.
  - get the full positron annihilation energy.
  - most of the neutron energy released after neutron capture.

Detector structure



- Buffer (stainless steel and PMT support, mineral oil):
  - reduce the single rate in target and gamma catcher.
  - Lower the positron threshold down to 500keV
- Inner veto (mineral oil): muon tagging and fast neutron background rejection.
- achieve a light yield about 200 pe/MeV
- Total PMT number 468 for each.

Experimental method

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

- Positron : deposits kinetic energy -> scintillation light and annihilation.

$$E_{\overline{\nu}_e} \cong 1.293(MeV) + E_{e^+}$$

- Neutrino
  - Neutron captures on hydrogen

$$n + p \rightarrow d + \gamma_{2.223MeV}$$

  - Neutron capture on Gd

$$n + Gd \rightarrow Gd^* + n\gamma_{8MeV} \ldots.$$

- Two energy need to be correlated in time and space->neutrino events

ANTINEUTRINO EVENTS PREDICTIONS

- $\overline{\nu}_e$ Spectrum from source β− decay

$${}_{92}U^{235} + n \rightarrow {}_{40}Zr^{94} + {}_{58}Ce^{140} + 2n$$

  - Electron spectra associated with the thermal neutron -> $\overline{\nu}_e$ spectra.

$$\frac{dN}{dE_e} \cong \frac{dN}{dE_{\overline{\nu}_e}}$$

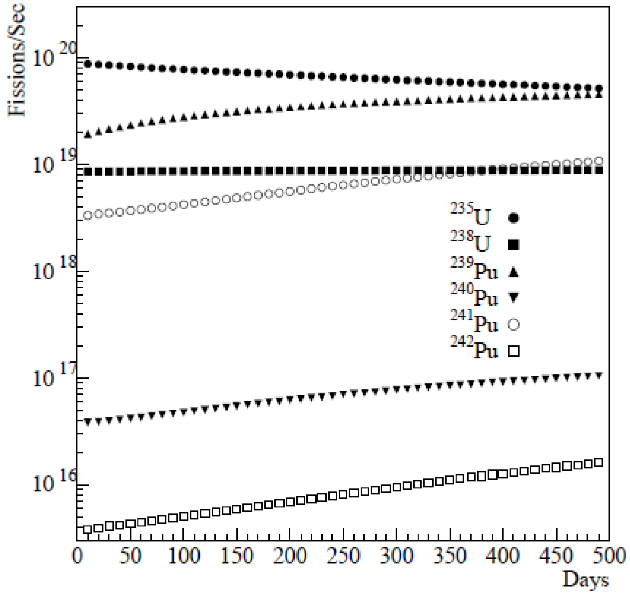


FIG. 6. Time evolution of fission rates for each of the six most important isotopes in one of the Palo Verde reactor cores. The horizontal scale covers a full fuel cycle, at the end of which about 1/3 of the core is replaced with fresh fuel. Only the four most important isotopes are normally used to predict $\bar{\nu}_e$ yields.

“Reactor-based Neutrino Oscillation Experiments“ Carlo Bemporad et al.

Antineutrino Events predictions(no oscillation)

- Antineutrino cross-section on proton

$$\langle \sigma \rangle_{fission} \cong 5.825 \times 10^{-43} cm^2$$

- Number of fission per second(Pth~4.27GWth,W~203.87MeV)
$$N_f = 6.241 \times 10^{18} \sec^{-1} \times \left(P_{th}\left[MW \right] / W\left[MeV \right] \right)$$
- Antineutrino events rate

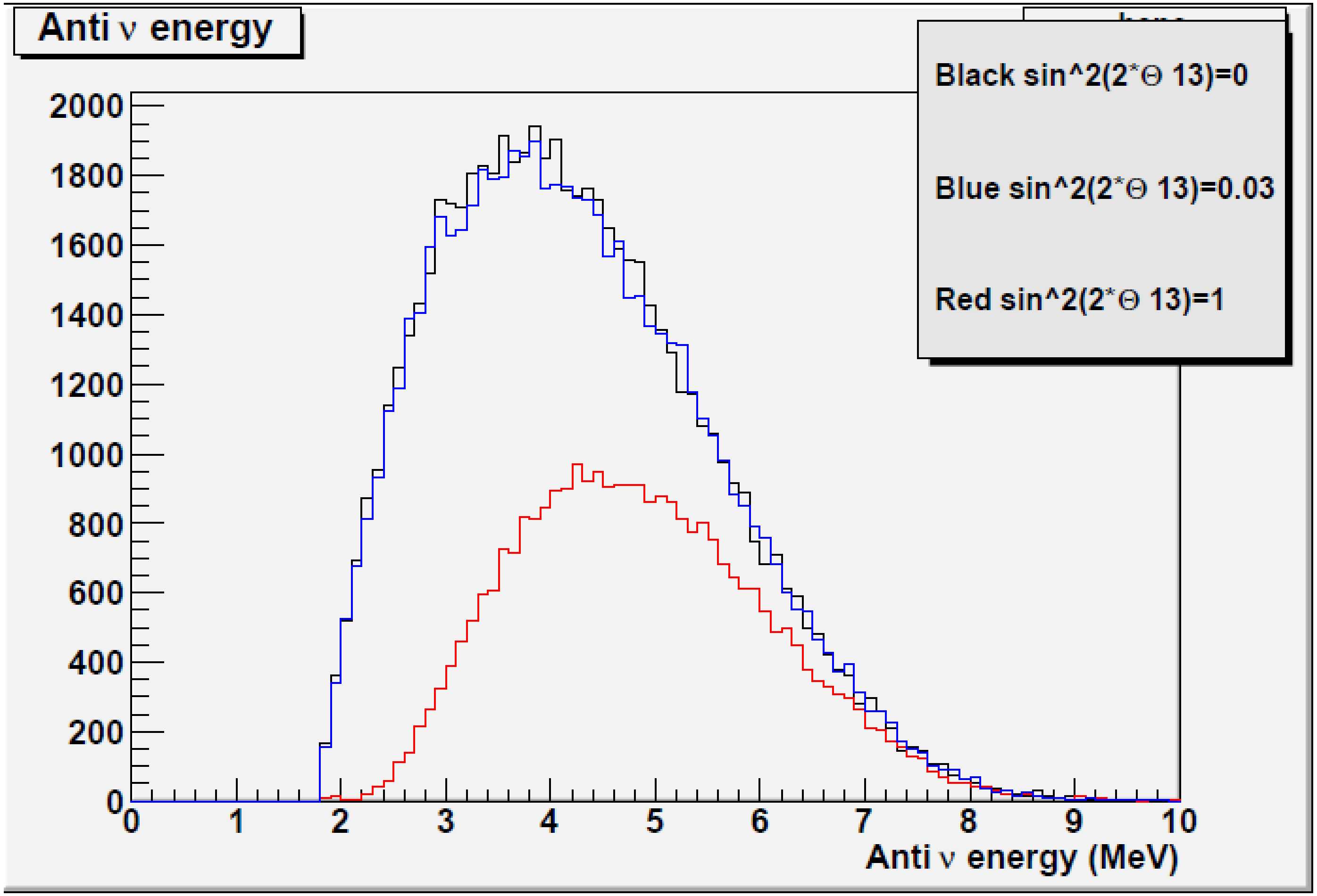
$$R_L = \frac{N_f \times \langle \sigma \rangle_{fission} \times n_p}{4\pi L^2} \cong 60 events / day$$

Antineutrino Events predictions(oscillation)

$$N_i = F\int_{E_i}^{E_{i+1}}\int_0^{+\infty} S(E_\nu, E'_\nu)\sigma(E_\nu)\phi_i(E_\nu, L)P_{\overline{\nu}_e\to\overline{\nu}_e}(E_\nu, L)dE_\nu dE'_\nu$$

- F: normalization factor
- S:energy resolution effect
- $\sigma(E_{e^+}) \cong \frac{2\pi^2\hbar^3}{m_e^5 f\tau_n} p_{e^+}E_{e^+}$, cross section for inverse β-decay
- φ: antineutrino flux
- P: antineutrino flux survival probability

1000days MC neutrino spectrum

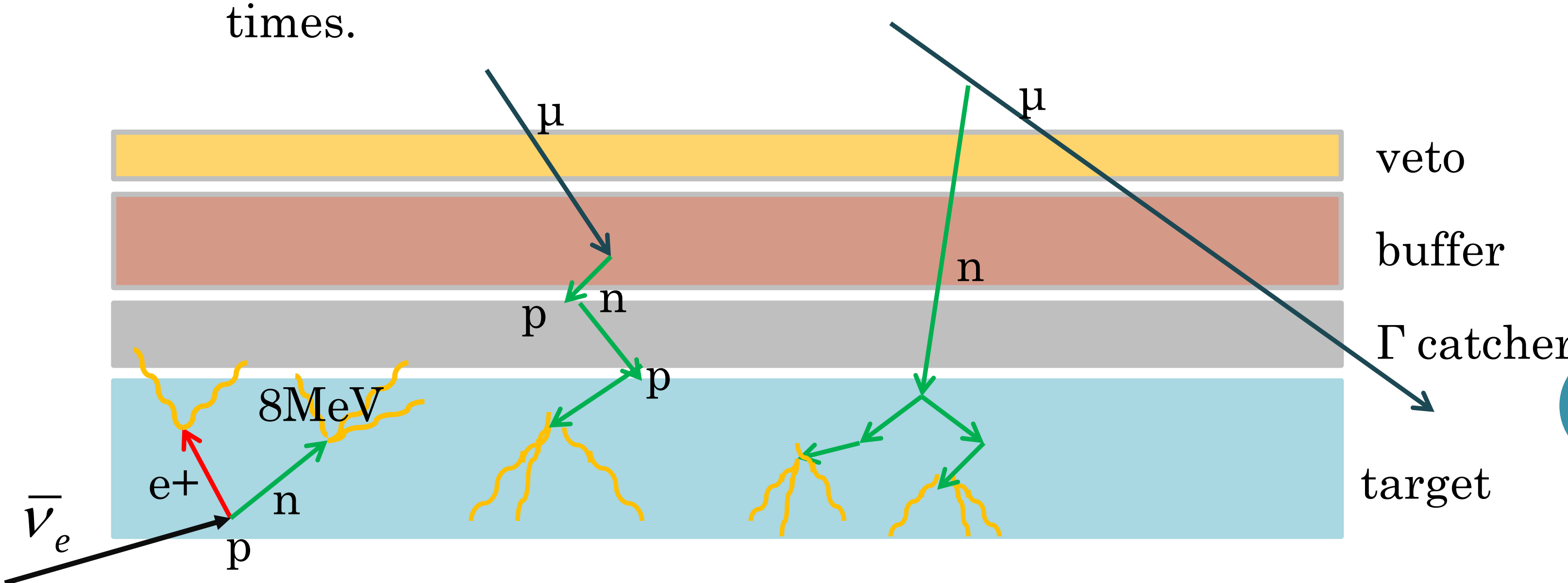


BACKGROUNDS

- $\bar{\nu}_e$ Interaction deposits at least1MeV and 8MeV neutron capture in gadolinium.
- Background -> neutron like events
  - Into time window(few 100 μs)
  - Over 1 MeV
- Beta and gamma background
  - U, Th and K from scintillator mass, acrylic vessels, photomultiplier and structure material.(>1MeV)
  - ^{208}Tl in buffer region 2.6MeV gamma emission.

NEUTRON BACKGROUND: NEUTRON LIKE EVENTS

- External cosmic muons
  - Through going muons -> spallation process
    - Estimated by muon fluxes, mean energies and shielding factors
  - Stopped negative muons ->captured by nuclei in target
    - Estimated by depth of shielding, μ-life time and μ-capture times.



- <u>Beta-neutron cascades</u>
  - Muon spallation on $^{12}C \rightarrow ^{8}He, ^{9}Li, ^{11}Li$ undergo beta decay with a neutron emission
- Uncorrelated muon events: one event per day for far and 9~23 events per day for near.

Experiment systematic uncertainties

- Main errors of CHOOZ
  - Antineutrino flux and spectrum(1.9%)
  - Cross section of neutrinos on the target protons.(0.8% number of protons, detector efficiency 1.5%)
- CHOOZ total error 2.7%->Double CHOOZ reduces to 0.6%.
  - reduce the systematic errors and background.
  - Two identical detectors ->negligible reactor flux and cross section of neutrinos on the target protons.

Analysis cuts to select the antineutrino

- 7 analysis cuts (CHOOZ)-> 3 analysis cuts
  - Reduce analysis cuts -> reduce uncertainty
- Prompt positron signal
  - Energy cut at 500keV and 200μs.(Antineutrino interaction least 1MeV)
- Neutron delayed signal, cut at 6MeV
  - Neutron capture on hydrogen at 2.2MeV
  - Neutron capture on gadoliniumat 8MeV
- neutron capture on gadolinium is less than 200μs.
- Prompt and delay event distance.(2m)

OTHER UNCERTAINTIES

- Solid angle
  - Distance between reactors and detectors.(keep below 0.2%)
- Uncertainty on the scintillator density
  - We need to know the mass of the target to <0.2%.
- Neutron efficiency(captured by H and Gd)

	CHOOZ	Double CHOOZ
Reactor power	0.7%	Negligible
Energy per fission	0.6%	Negligible
Antineutrino/Fission	0.2%	Negligible
Neutrino cross section	0.1%	Negligible
Number of protons/cm3	0.8%	0.2%
Neutron time capture	0.4%	Negligible
Neutron efficiency	0.85%	0.2%
Neutron energy cut	0.4%	0.2%

SENSITIVITY

- Least squares Minimization

$$m_i = t_i(\vec{p}) + r_i \sigma_i + \sum_k s_k \Delta_{ik}$$

  - m: measurement of data-background, t: the model prediction, σ: the uncorrelated (statistical)error, Δ:correlated(systematic error) from source k.

- Probability density function of measurements
-

$$P = C \exp\left(-\frac{1}{2}\chi^2\right), \chi^2 = \sum_{ij}\left(\frac{m_i}{t_i} - 1\right) V_{ij}^{-1} \left(\frac{m_j}{t_j} - 1\right), V_{ij} = \delta_{ij}\sigma_i^2 + \sum_k \Delta_{ik}\Delta_{jk}$$

- Correlated : theoretical cross section of detector, reactor fluxes(spectrum of antineutrino flux)
- Uncorrelated: proton numbers, baseline lengths, a part of detector efficiency, background..

Sensitivity models

- one detector one reactors model

$$\chi^2 = \left(\frac{m}{t}-1\right)V^{-1}\left(\frac{m}{t}-1\right) = \frac{\left[\left(m/t-1\right)\right]^2}{\sigma_c^2+\left(\sigma_u^{(r)}\right)^2+\left(\sigma_c^{(r)}\right)^2+\sigma_u^2}$$

$$\cong \frac{\sin^4 2\theta\left(\left\langle \sin^2\left(\frac{\Delta m^2 L}{4E}\right)\right\rangle\right)^2}{\sigma_c^2+\left(\sigma_u^{(r)}\right)^2+\left(\sigma_c^{(r)}\right)^2+\sigma_u^2}, V = \sigma_c^2+\left(\sigma_u^{(r)}\right)^2+\left(\sigma_c^{(r)}\right)^2+\sigma_u^2$$

$$\left\langle \sin^2\left(\frac{\Delta m^2 L}{4E}\right)\right\rangle = F\int_{E_i}^{E_{i+1}}\int_0^{+\infty} S(E_\nu, E'_\nu)\sigma(E_\nu)\phi_i(E_\nu, L)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)dE_\nu dE'_\nu$$

Form : “Systematic limit on $\sin^2 2\theta_{13}$ in neutrino oscillation experiments with multi-reactor” H. Sugiyama et al.

SENSITIVITY MODELS

- two detector one reactor model

$$\chi^2 = \left(\frac{m_n}{t_n} - 1, \frac{m_f}{t_f} - 1 \right) V^{-1} \begin{pmatrix} \frac{m_n}{t_n} - 1 \\ \frac{m_f}{t_f} - 1 \end{pmatrix} = \frac{\left[(m_n/t_n - 1) + (m_f/t_f - 1) \right]^2}{4\sigma_c^2 + 4\left(\sigma_u^{(r)}\right)^2 + 4\left(\sigma_c^{(r)}\right)^2 + 2\sigma_u^2} + \frac{\left[(m_n/t_n - 1) - (m_f/t_f - 1) \right]^2}{2\sigma_u^2}$$

$$\cong \sin^4 2\theta \left[\left(\left\langle \sin^2\left(\frac{\Delta m^2 L_f}{4E} \right) \right\rangle - \left\langle \sin^2\left(\frac{\Delta m^2 L_n}{4E} \right) \right\rangle \right)^2 \Big/ 2\sigma_u^2 \right]$$

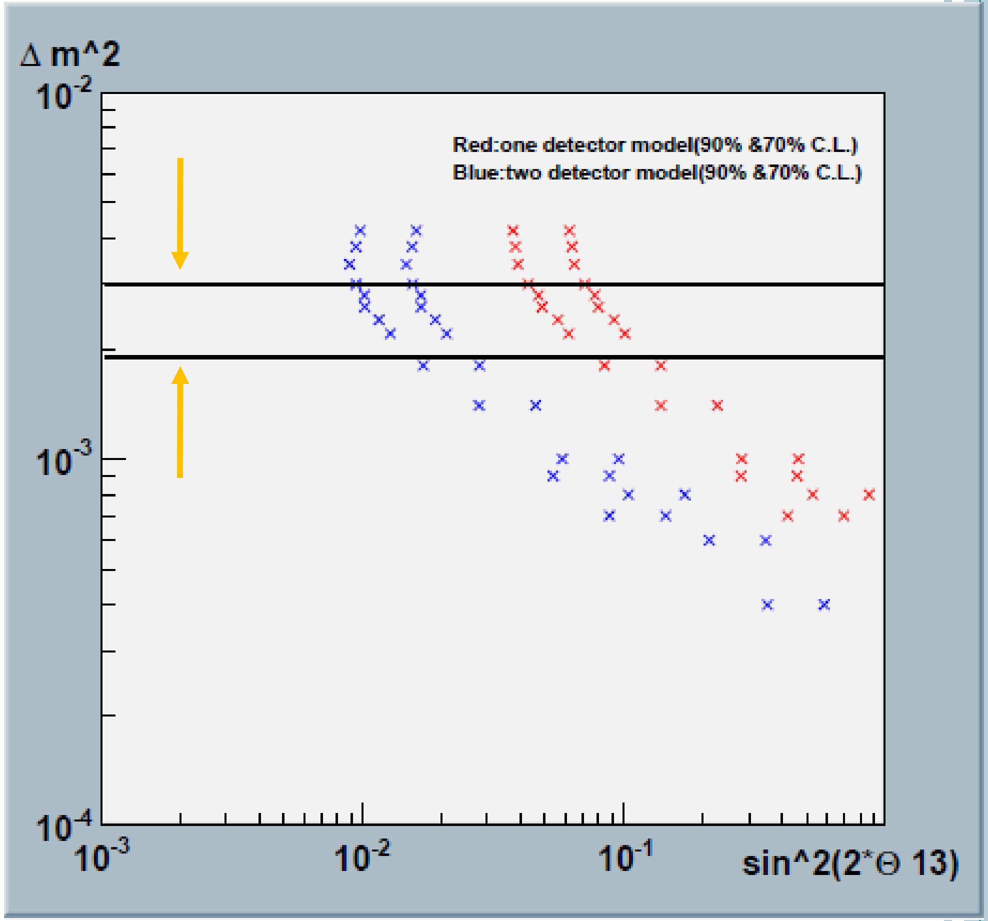
Form : “Systematic limit on $\sin^2 2\theta_{13}$ in neutrino oscillation experiments with multi-reactor” H. Sugiyama et al.

Sensitivity of $\sin^2 2\theta_{13}$ (one detector vs. two detector one reactor model)

- 100days MC data,

$$\Delta m^2_{31} = 2.4^{0.6}_{-0.5} \times 10^{-3} eV$$

	90% C.L.	70% C.L.
Two detector	0.02~0.015	0.0127~0.009
One detector	0.10~0.07	0.06~0.04



Recent work: Energy scale

- To reconstruct the conversion function between a measurable detector quantity and energy.
- processes
  - The energy of measured particles
    - Quenching of the scintillation light
    - Cerenkov light

$$\left.\frac{E_{visible}}{E_{real}}\right|_{\gamma}(E) = S\left[Q_{\gamma}(K_b, E) + C_{\upsilon} P_{\gamma}(E)\right]$$

"A precise determination of the Kamland energy scale" Timothy M. Classen thesis.

Scintillator

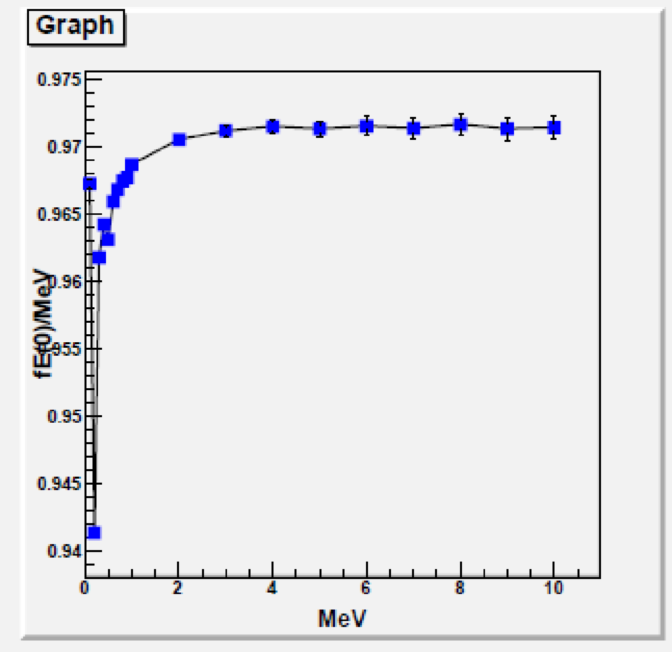
- Solvents
  - 20% PXE($C_{16}H_{18}$) :collect energy, conduct energy to fluor.
  - 80% of dodecane($C_{12}H_{26}$): improve the chemical compatibility with the acrylic, increase the number of free protons.
- Fluor (0.3~1%)
  - Primary-> PPO(emission λ 357 nm): able to be excited to a light emitting state by excited solvent molecules.
  - Secondary-> Bis-MSB(emission λ 420 nm): wavelength shifter.

Ionization Quenching

- When a large amount of energy is deposited in a small area , some of molecules in scinllator will shed their excess energy thermally through a quenched energy.
- Birks' Law

$$\frac{E_{visible}}{E_{real}} = \frac{S}{E_{real}} \int_0^E \frac{dE}{1 + K_b \frac{dE_c}{dx}}$$

- Kb is Birks' constant, S scintillation efficiency, E is particle energy, and x is the range in scintillator.

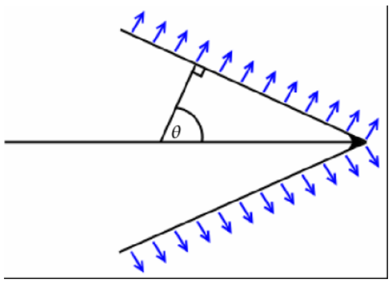


Simulation by MC

"A precise determination of the Kamland energy scale" Timothy M. Classen thesis.

Cerenkov light

- Cerenkov radiation is produced whenever a charged particle is traveling faster than the local speed of light.

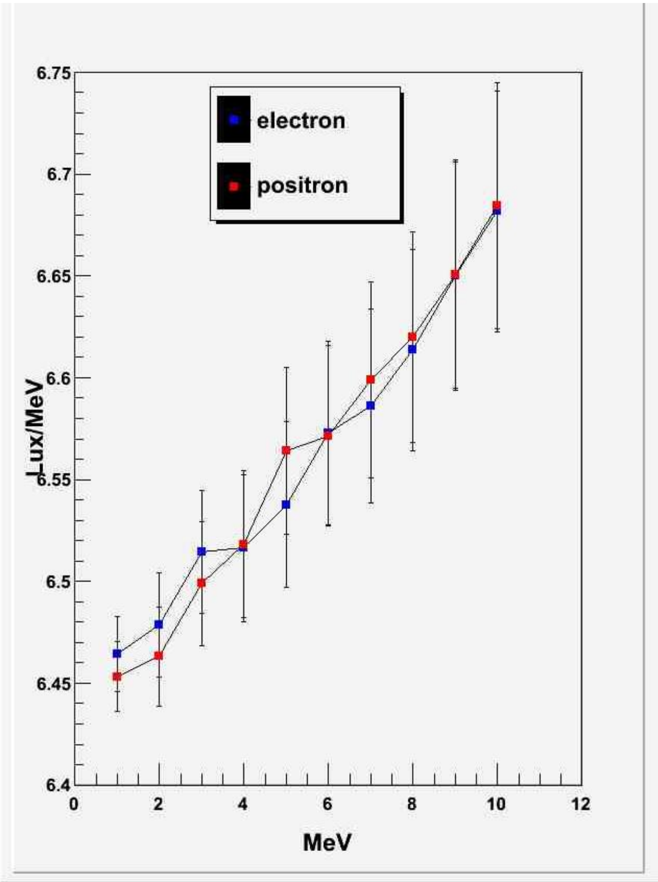


$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right)$$

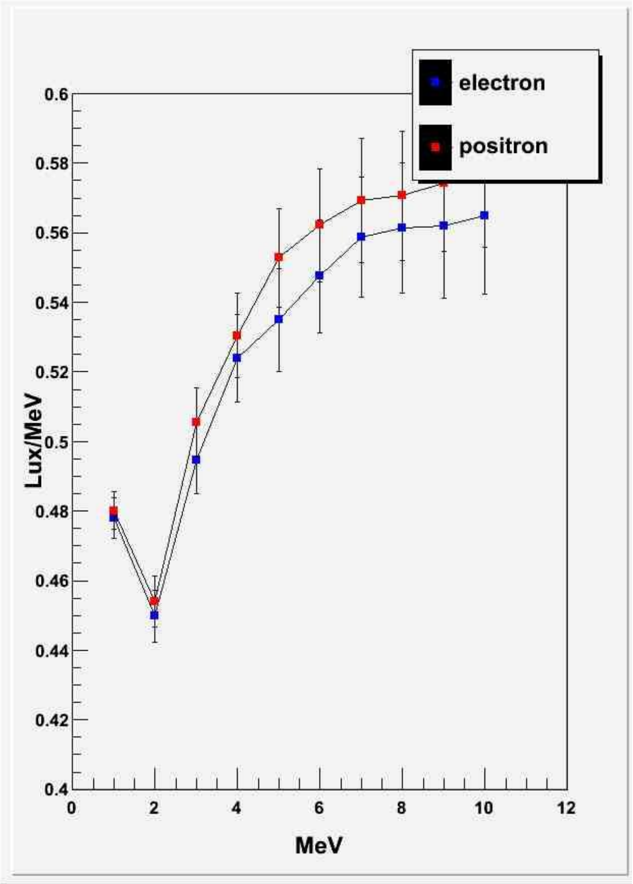
- N is number of photons, x is track length, α is the fine structure constant and z is the particle's charge.
- The light will absorb by PXE and reemit by fluor

Quench and Cerenkove light flux in detector

Only Quench light



Only Cerenkov light

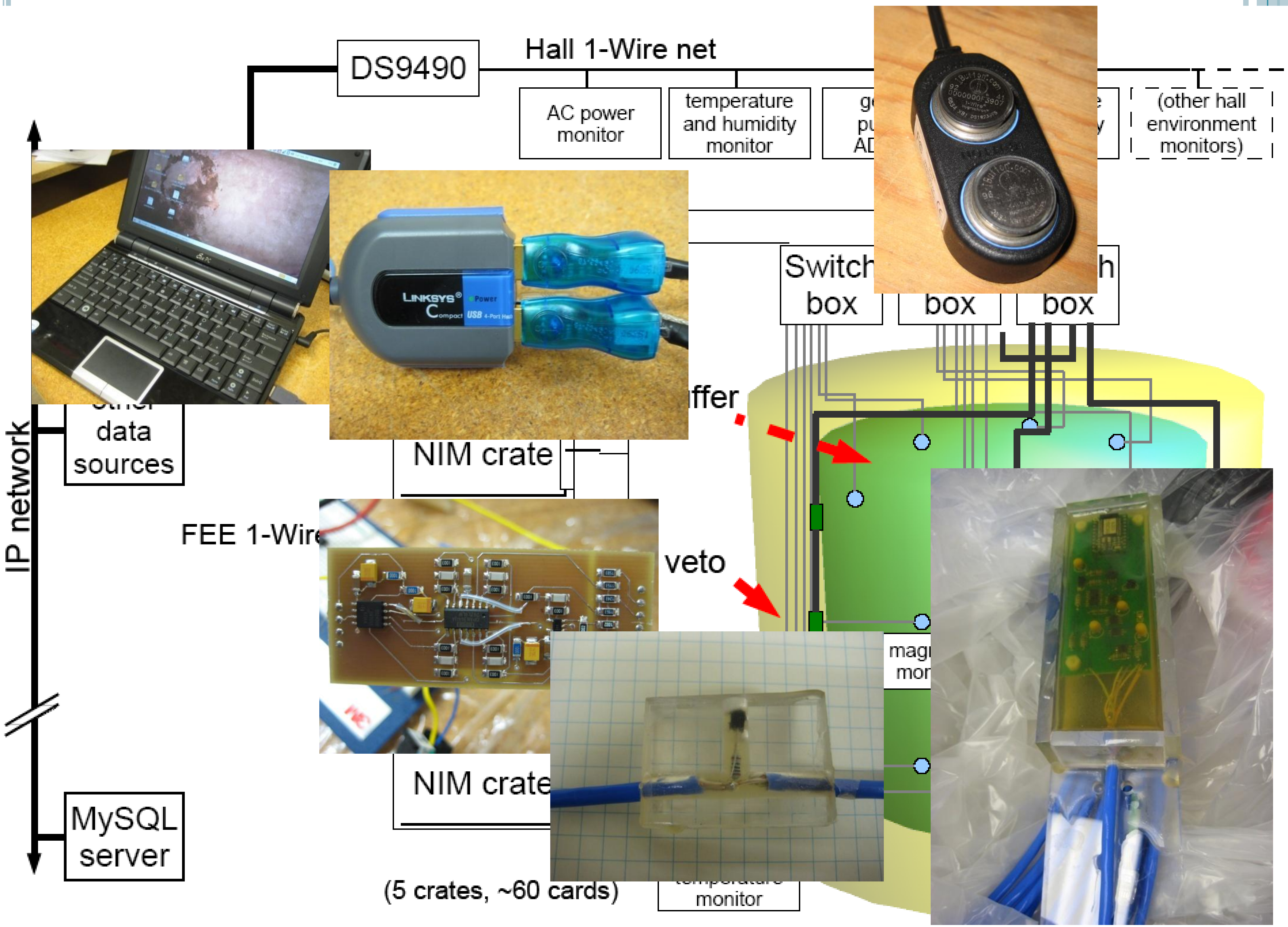


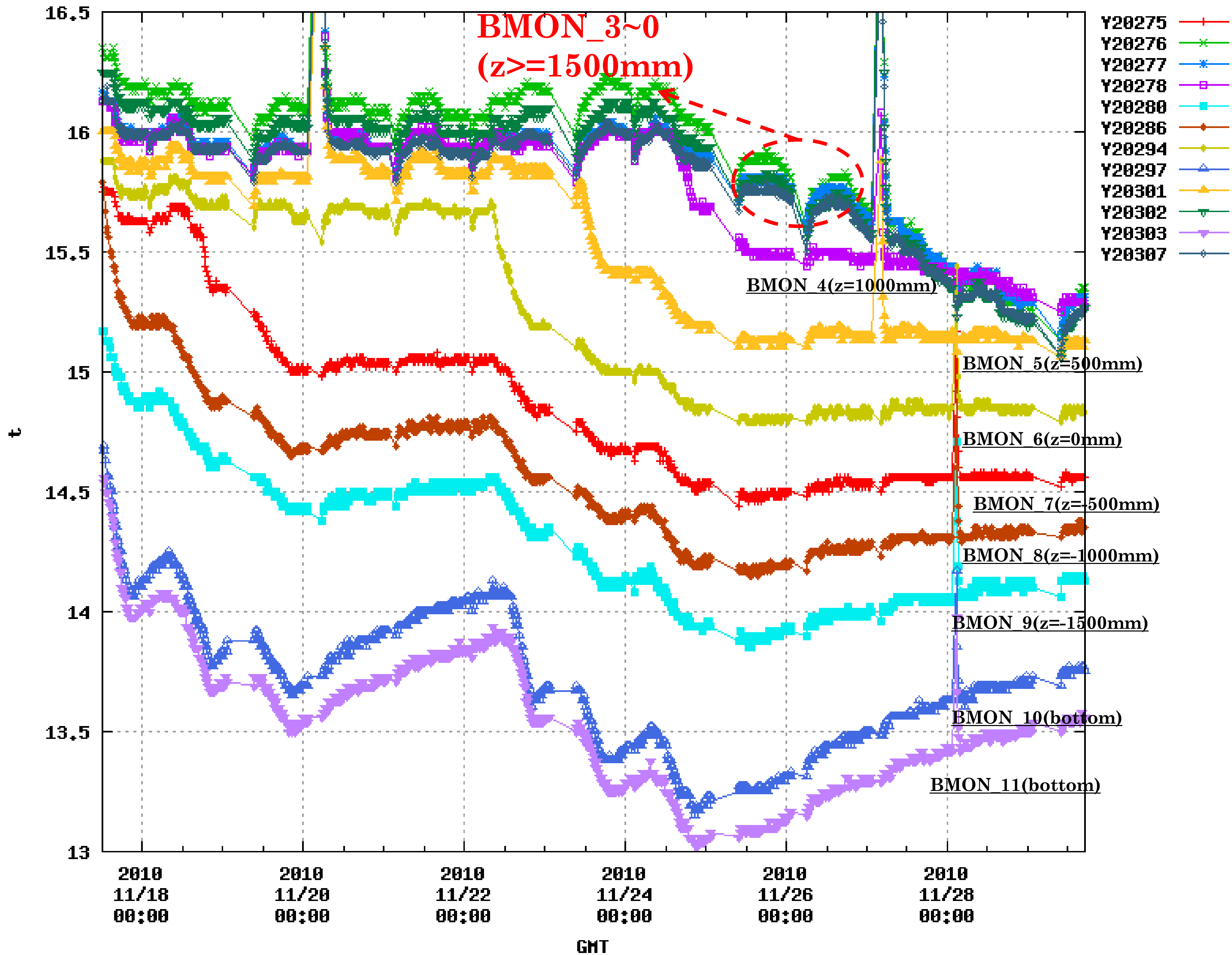
Energy scale work

- Quench
  - the quenching bench measurements->Values of Birk's parameter Kb for MC .
  - Calibration source natural alpha sources-> produce no Cerenkov light.
  - Compare calibration data->adjust Kb constants.
- Cerenkov light
  - Calibrated by Compton scattering

Recent work: environmental monitoring

- “Slowmon system”, environmental monitoring system installation is done in far detector.
  - environmental monitoring system, Control systematic effects and Provide alarms, warnings, diagnostics
  - Detected items: temperature, magnetic field around PMT, voltage values of Front-end boards and hall and control room temperature and humidity.


DS9490
Hall 1-Wire net
AC power monitor
temperature and humidity monitor
(other hall environment monitors)
Switch box
box
box
IP network
data sources
NIM crate
veto
NIM crate
MySQL server
(5 crates, ~60 cards)
monitor
LINKSYS
Compact
USB
Power



BMON_3~0
(z>=1500mm)
BMON_4(z=1000mm)
BMON_5(z=500mm)
BMON_6(z=0mm)
BMON_7(z=-500mm)
BMON_8(z=-1000mm)
BMON_9(z=-1500mm)
BMON_10(bottom)
BMON_11(bottom)
Y20275
Y20276
Y20277
Y20278
Y20280
Y20286
Y20294
Y20297
Y20301
Y20302
Y20303
Y20307
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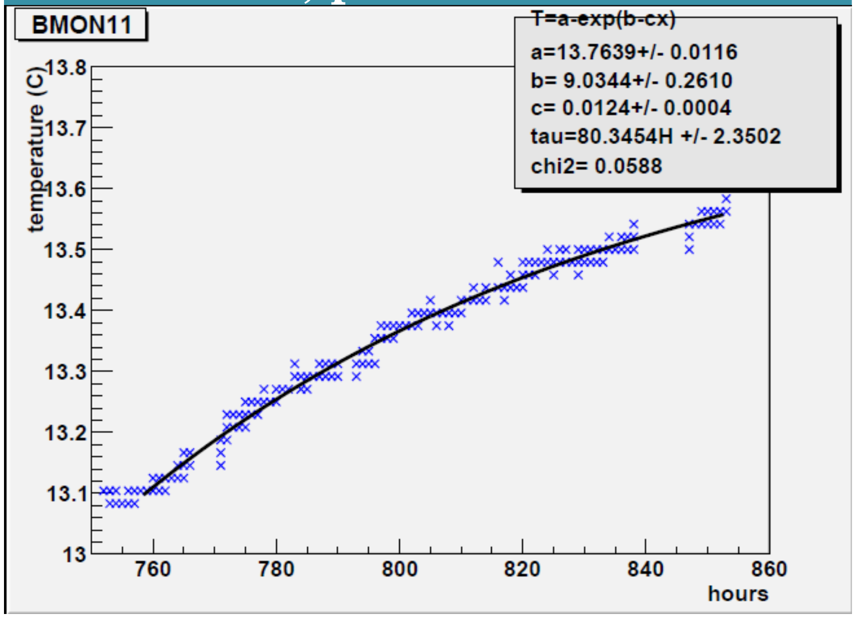
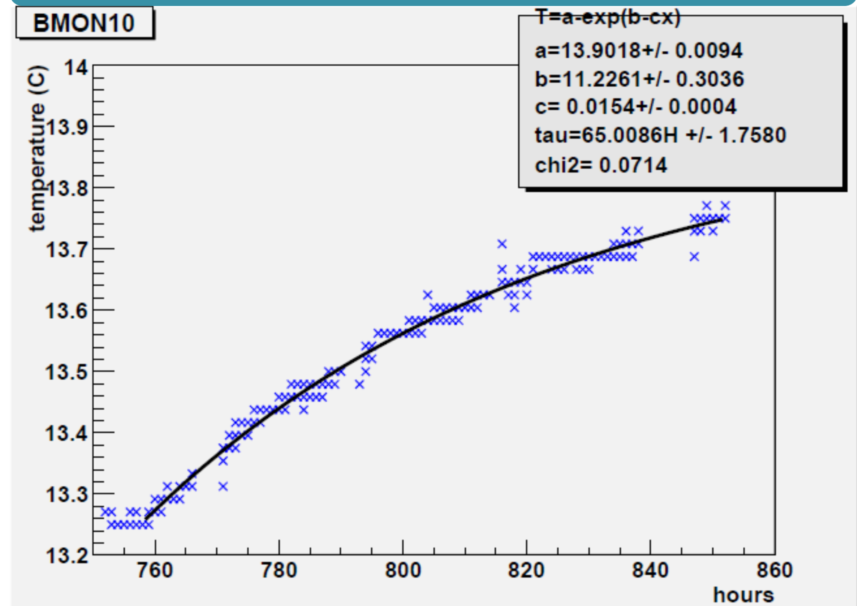
2010 11/18 00:00
2010 11/20 00:00
2010 11/22 00:00
2010 11/24 00:00
2010 11/26 00:00
2010 11/28 00:00
GMT

Buffer tank thermal meters data from 11/25~11/29

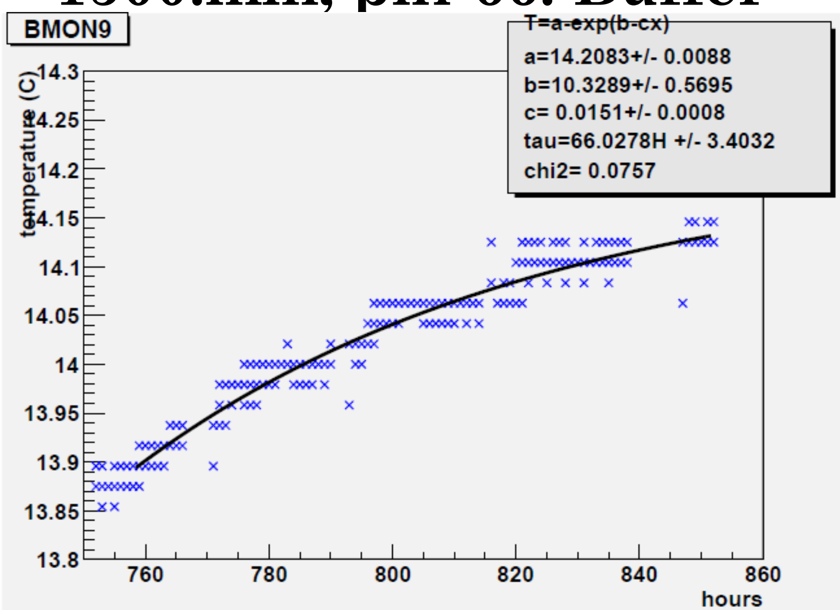
-2831.4mm, phi141.6 Buffer



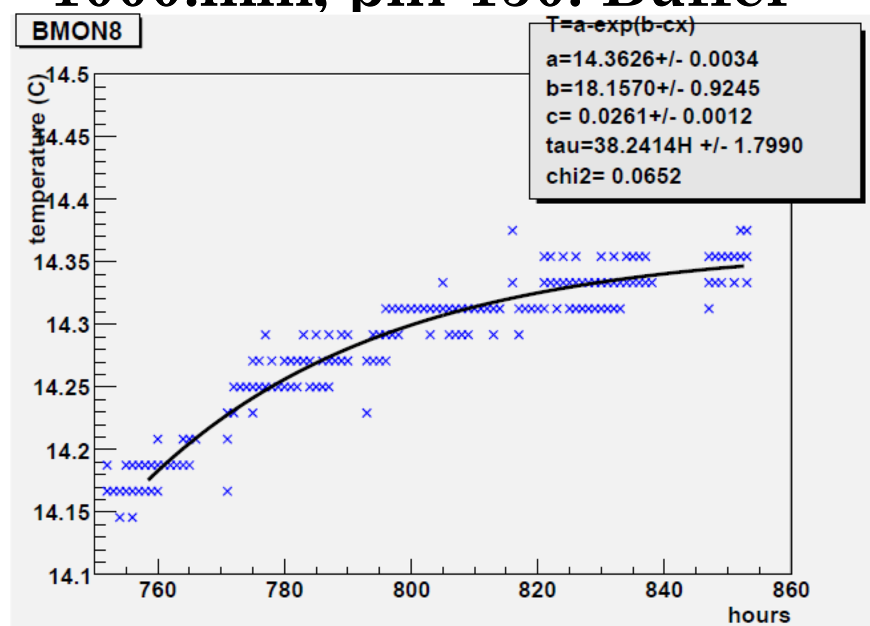
-2804.5mm, phi 86.3 Buffer



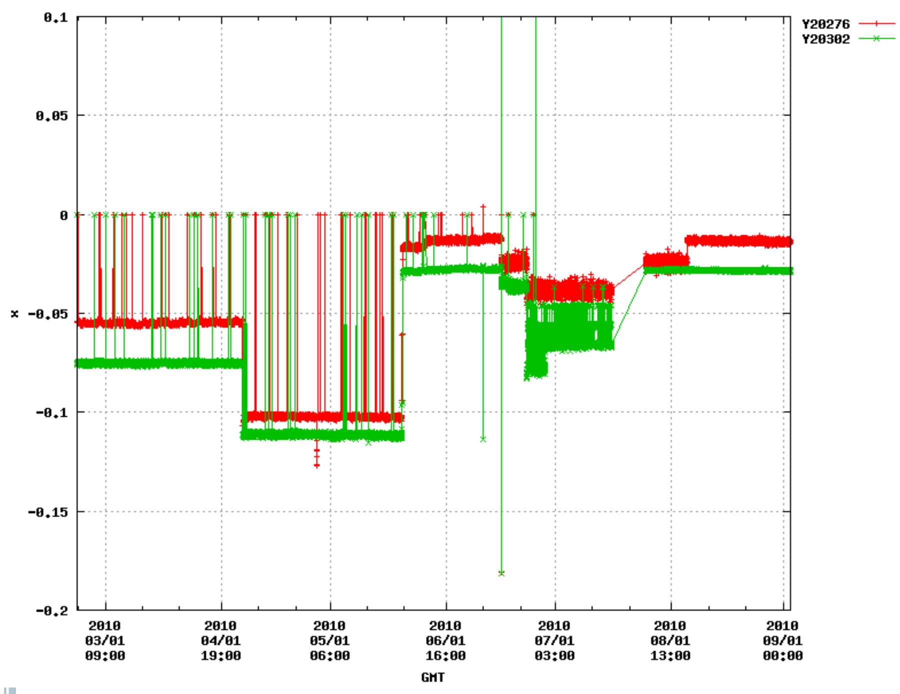
-1500.mm, phi-66. Buffer

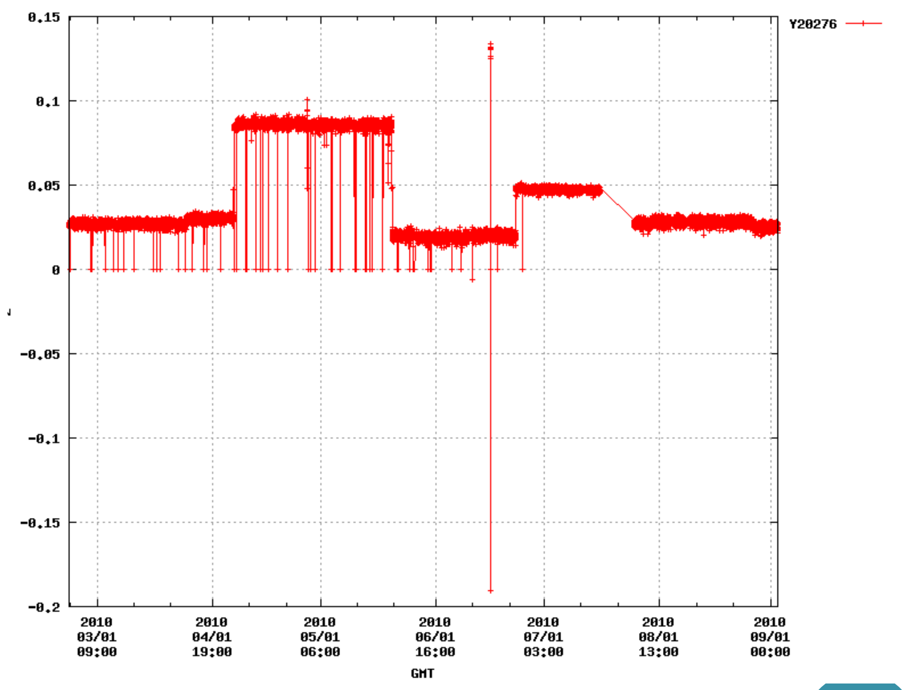


-1000.mm, phi-150. Buffer



MAGNETIC FIELD IN BUFFER TANK FROM 2/21~9/2





Recent process

- Temperature Auto-warning system is done in lab
- Filling process (especial target tank)depend on the temperature changing in the tanks.
- Magnetic monitoring is proved working well in IV lid open period.
- IV and Buffer thermal data-> thermal model of detector-> proton number.

FINAL FITTING PROCESS

- Constructing a Covariance Matrix

$$P = C\exp\left(-\frac{1}{2}\chi^2\right), \chi^2 = \sum_{ij}\left(\frac{m_i}{t_i}-1\right)V_{ij}^{-1}\left(\frac{m_j}{t_j}-1\right), V_{ij} = \delta_{ij}\sigma_i^2 + \sum_k \Delta_{ik}\Delta_{jk}$$

  - Parameters determined directly from calib. Data
  - Parameters should be simultaneously varied in MC to match calib. Data

CONCLUSION

- 3 mass eigenstate model is the simplest model to explain three flavor neutrino oscillation
- Reactor neutrino experiment advantages
  - Doesn't depend on the δ-CP phase
  - Uniform antinutrino flux
  - no CP if $\sin^2\theta_{13} \to 0$
- Double Chooz experiment
  - Near detector-> raise sensitivity from Sensitivity models $\sin^2\theta_{13} \cong 0.02 \sim 0.015$
  - Buffer range -> reduce background and threshold energy

CONCLUSION

- Recent work
  - Environmental monitoring
    - Hardware and database are done
    - Thermal information analysis for filling system
    - Warning system
    - Thermal model of detector-> number of protons in detector
  - Energy scale and final fitting
    - Parameters determined directly from calib. Data
    - Constructing a Covariance Matrix

REFERENCE

- "Double Chooz: A Search for the Neutrino Mixing Angle θ13" F. Ardellier et al. http://arxiv.org/PS_cache/hep-ex/pdf/0606/0606025v4.pdf
- "Letter of Intent for Double-CHOOZ: a Search for the Mixing Angle θ13" F. Ardellier et al. http://arxiv.org/PS_cache/hep-ex/pdf/0405/0405032v1.pdf
- "Reactor-based Neutrino Oscillation Experiments" Carlo Bemporad et al. arXiv:hep-hp/0107277 v1
- "Systematic limit on $\sin^2 2\theta_{13}$ in neutrino oscillation experiments with multi-reactor" H. Sugiyama et al.
- "Error Estimates on Parton Density Distributions" M Botje et al.
- "A precise determination of the Kamland energy scale" Timothy M. Classen thesis.
- "Neutrino Phenomenology Facts, and Question" Boris Kayser 2009 neutrino summer school

Systematic errors

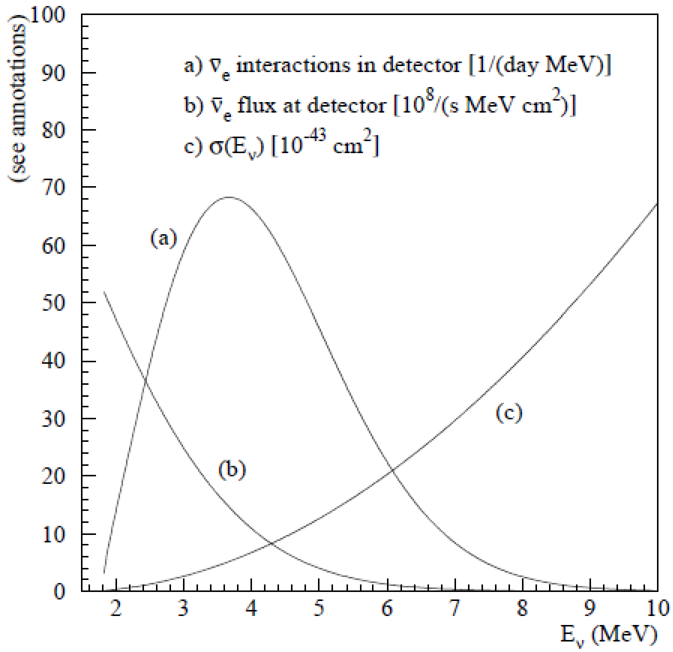
- Global normalization error: uncertainty of antineutrino flux and detector cross section(no impact)
- Relative normalization error: experiment error, uncertainties on the detector design and event select cuts.
- Spectral shape error: antineutrino spectrum shape ->the energy bin we take.
- Energy scale: energy scale calibration uncertainty of visible energy(seen in the detector)
- Background subtraction step: only one uncorrelated error

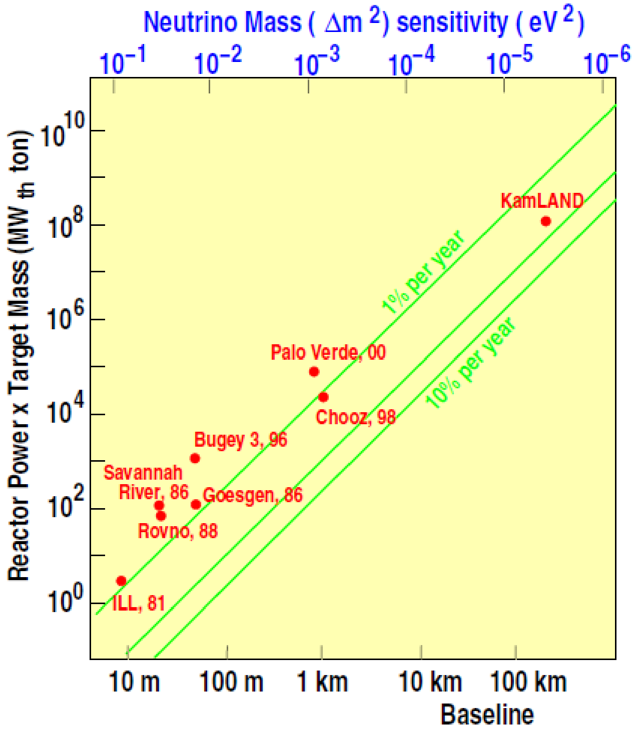
Error type	
Global normalization	2%
Relative normalization	0.6%
Spectrum shape	2%
Energy scale	0.5%
background	0.5%

REACTOR NEUTRINO EXPERIMENT PROPERTIES

flux and cross section

Neutrino Δm^2 sensitivity

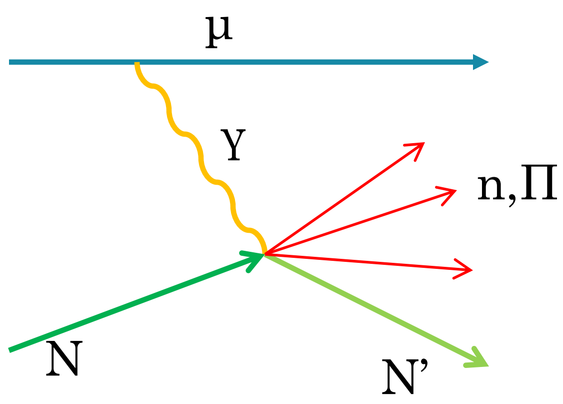




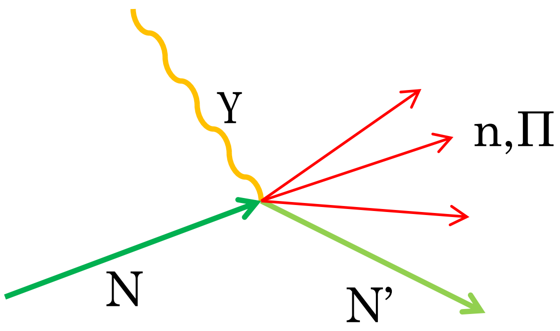
"Reactor-based Neutrino Oscillation Experiment" Carlo Bemporad et al.

Muon spallation and photo-absorption

- spallation



- Photo-absorption



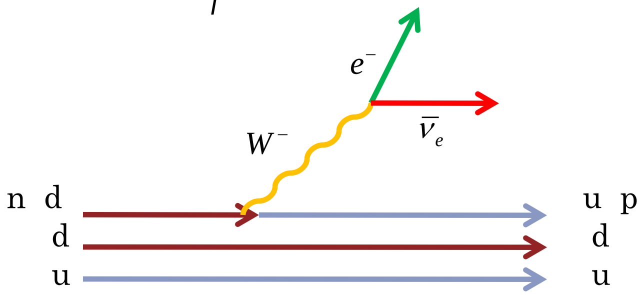
Cross section for neutrino absorption

- Reaction rate

$$dW_r \equiv JN \frac{d\sigma_r(\theta,\phi)}{d\Omega} d\Omega = \frac{2\pi}{V} \rho(E_f) |m_{if}|^2, \rho(E_f) = \frac{V q_f^2}{8\pi^3 v_f} d\Omega$$

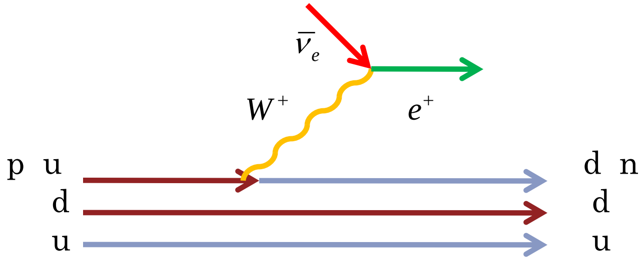
- $n \to p + e^- + \bar{\nu}_e$ cross section

$$\frac{d\sigma}{d\Omega} = \frac{2\pi}{\hbar c} G_F^2 \left\langle |m_{fi}|^2 \right\rangle \left[\frac{p_e E_e}{(2\pi\hbar)^3 c^2} \right] \left[\frac{p_{\bar{\nu}}^2}{(2\pi\hbar)^3 c^2} \right]$$



- $\bar{\nu}_e + p \to n + e^+$ cross section

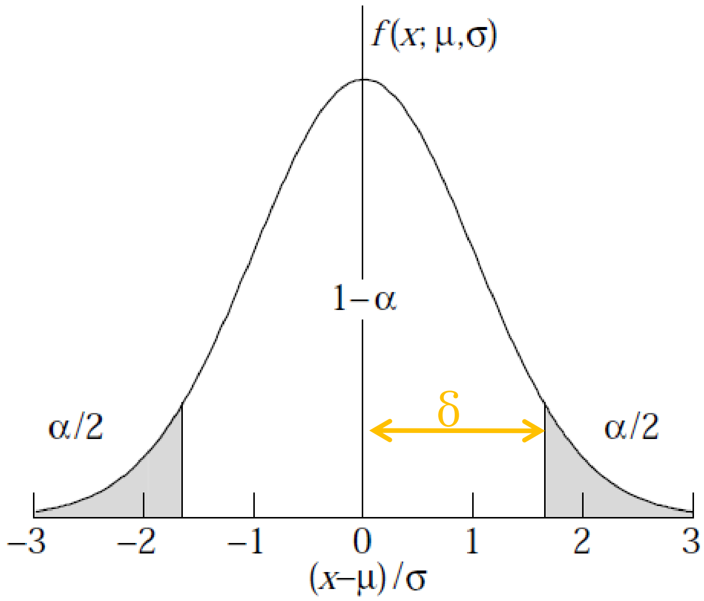
$$\frac{d\sigma}{d\Omega} = \frac{2\pi}{\hbar c} G_F^2 \left\langle |m_{fi}|^2 \right\rangle \left[\frac{p_{e^+} E_{e^+}}{(2\pi\hbar)^3 c^2} \right]$$



Confidence interval

- 90%=1.28σ
- 68.27%~ σ

α	δ
0.3173	1σ
0.2	1.28σ
0.1	1.64σ
0.05	1.96σ
0.01	2.58σ
0.001	3.29σ
0.0001	3.89σ



From: Revised September 2009 by G. Cowan (RHUL).

The method of least squares

- LS estimator ->minimum of

$$\chi^2(\theta)=(m-t(\theta))^T V^{-1}(m-t(\theta))$$

- Chi^2 is equal to zero->LS estimators

$$t(x_i;\vec{\theta})=\sum_{j=1}^{m}\theta_j h_j(x_i);\hat{\theta}=\left(H^T V^{-1} H\right)^{-1} H^T V^{-1}\vec{m}\equiv D\vec{m}=U\vec{g}$$

$$U=DVD^T\left(H^T V^{-1} H\right)^{-1};g_i=\sum_{j,k=1}^{N} m_j h_i(x_k)\left(V^{-1}\right)_{jk}$$

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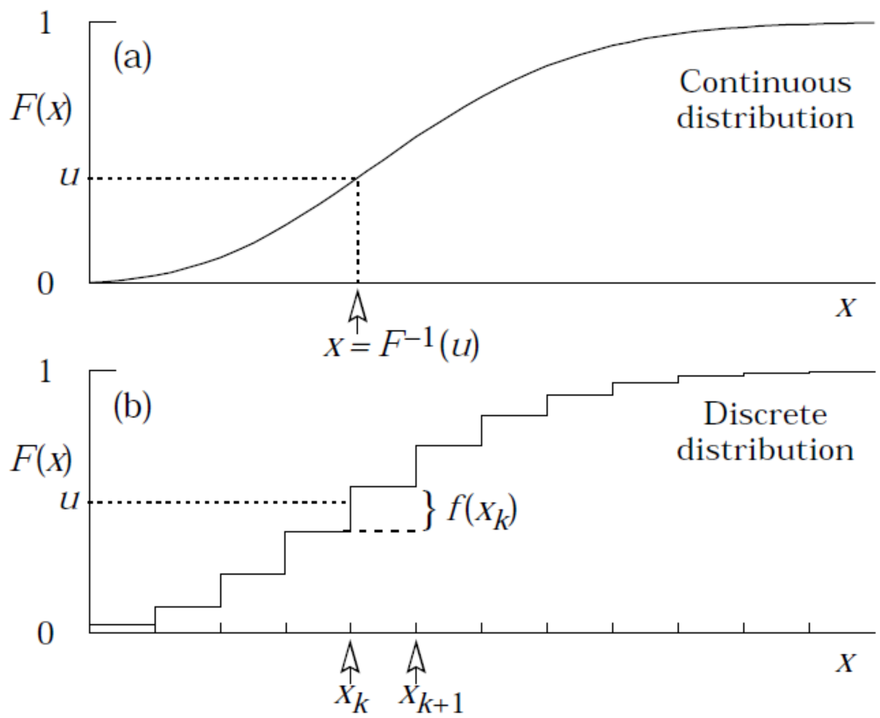
Monte carlo techniques

- Sample random variables governed by complicated probability density function
- F(x) is a uniform distribution (0,1)
- f(x) desired probability density function.



$$u = F(x)$$

$$x = F^{-1}(u)$$

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