Daya Bay

Steve Kettell
BNL

1) Motivation
2) Daya Bay Experiment
3) Daya Bay Project
4) BNL involvement
**The Last Mixing Angle: $\theta_{13}$**

$U_{\text{MNSP}}$ Matrix  
Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

atmospheric, K2K  
reactor and accelerator  
SNO, solar SK, KamLAND  
$0\nu\beta\beta$

$\theta_{23} = \sim 45^\circ$  
$\theta_{13} = ?$  
$\theta_{12} \sim 32^\circ$

What is $\nu_e$ fraction of $\nu_3$?  
Is there $\mu-\tau$ symmetry in neutrino mixing?  
$U_{e3}$ is the gateway to leptonic CP violation.
Why BNL?

• The Physics is compelling! and a critical step to CP
• BNL provides a strong National Laboratory presence to assure the success of the experiment.
• BNL has a rich tradition in $\nu$ physics: in both the Physics and Chemistry departments
• BNL Chemistry has been involved in liquid scintillator research for Daya Bay for 3 years
• This experiment is a good match to the existing Physics Department effort on MINOS and future long-baseline experiment to measure CP violation in the neutrino sector.
Measuring $\sin^2 2\theta_{13}$ with Reactor Neutrinos

$$P_{ee} \approx \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

- No dependence on $\delta_{CP}$ or matter effects
- Cost effective
- Rapid deployment possible

Daya Bay, China

~1.8 km
~0.3-0.5 km

Distance (km)

Probability

detector 1

detector 2

$\theta_{13}$
Detection of antineutrinos in liquid scintillator

- inverse $\beta$-decay in Gd-doped liquid scintillator:
  $$\bar{\nu}_e + p \rightarrow e^+ + n \text{ (prompt)}$$

  0.1% Gd

  \[ 0.3b \rightarrow + p \rightarrow D + \gamma(2.2 \text{ MeV}) \text{ (delayed)} \]

  \[ 50,000b \rightarrow + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma's(8 \text{ MeV}) \text{ (delayed)} \]

- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of $\bar{\nu}_e$ is given by:
  $$E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8 \text{ MeV}$$
  10-40 keV

From Bemporad, Gratta and Vogel
At $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} < 0.17$.

- **Allowed Region**
  - ~3000 events in 335 days
  - 2.7% systematic error without near detectors

**Daya Bay** takes ~1 week
Sensitivity to $\sin^2 2\theta_{13} \leq 0.01$

High statistics:
- Powerful reactor cores
- Large target mass

Control of systematic errors:
- Utilize multiple detectors at different baselines (near and far) → measure RATIOS
- Make detectors as nearly IDENTICAL as possible
- Careful and thorough calibration and monitoring of each detector
- Optimize baseline for best sensitivity and small residual reactor-related errors
- Possible to interchange detectors to further cancel most detector systematics
Measure ratio of detector rates:

\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]
\]

Measured Ratio of Rates

Detector Mass Ratio, H/C

Fill in pairs, load cells, Coriolis mass flow to 0.2% repeatability

Detector Efficiency Ratio

\[\sin^2 2\theta_{13}\]

Requirement: know relative efficiencies, each to 0.2%.
Antineutrino Detector

- Antineutrinos are detected via inverse $\beta$-decay in Gd-doped liquid scintillator (LS)

Description:
- 3 zones: Gd-LS target (20 tons), LS gamma catcher, oil buffer
- 2 nested acrylic vessels, 1 stainless vessel
- 192 PMT’s on circumference of $5m \times 5m$ cylinder
- reflectors on endplates of cylinder
- energy resolution:

$$\frac{\sigma}{E} \sim \frac{11.6\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{\text{vertex}} = 12.5\text{cm}$$
Muon System

- Muon Veto
  - suppress spallation neutrons
  - require 99.5% efficiency

- Water shield (2.5m)
  - rock neutrons
  - radioactivity

- Water Cherenkov detectors with 963 PMTs in 3 sites
- 756 RPC chambers over top of 3 pools (6048 readout strips)
Daya Bay Nuclear Power Facilities

- World’s 12th most powerful (11.6 GWth)
- 5th most powerful by 2011 (17.4 GWth)
- Adjacent to mountains, facilitates tunnels to underground labs with sufficient overburden to suppress cosmic rays (flexibility to move detectors)

1 GWth generates $2 \times 10^{20} \nu_e$ per sec

Ling Ao II NPP: $2 \times 2.9$ GWth
Ready by 2010-2011

Ling Ao NPP: $2 \times 2.9$ GWth

Daya Bay NPP: $2 \times 2.9$ GWth
Daya Bay

Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Mid site
~1000 m from Daya
Overburden: 208 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Ling Ao-ll NPP
(under const.)

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Total length: ~2700 m
Sensitivity

- Far hall (80 t)
- Ling Ao near hall (40 t)
- Tunnel entrance
- Daya Bay near hall (40 t)

3-year run with 80 t at far site

- Use rate and spectral shape
- Input relative detector systematic error of 0.2%

Brookhaven National Laboratory

4/17/2007

DOE HEP Review: Steve Kettell
Daya Bay Project Status

- CD-0: 11/2005
- BNL formally joins collaboration 2/2006
- Project team assembly begins 2/2006
- NuSAG endorses DB goal and DB expt. as one option 2/2006
- DOE Daya Bay Briefing 4/2006, R&D funds approved
- Successful Physics Review 10/16-17/06
- P5 Roadmap: Recommends Daya Bay 10/2006
- **Successful CD-1 Review 4/10-11/07**
- Start of Civil construction 7/2007
- CD-2 Baseline planned for 10/2007
- CD-3b Construction start planned for Spring 2008
- CD-4b start of full operations fall 2010
Internal Project Organization

- **LBNL Underground Experimental Safety Review Committee**
  - B. Edwards (PM)
  - S. Kettell (CS)

- **PAP**
  - G. Gilchriese
  - D. Lissauer

- **Executive Board**
  - K.B. Luk (Co-SP)
  - Y.F. Wang (Co-SP)

- **US Project Office**
  - Y.F. Wang (PM)
  - B. Edwards (PM)
  - S. Kettell (CS)

- **PRC Project Office**
  - Y.F. Wang (PM)
  - Y.F. Wang (Co-SP)

- **Technical Board (TB)**
  - R. Brown
  - H.L. Zhuang

- **Underground Construction**
  - C. Laughton
  - (consultant)

- **US-DYB Safety Office**
  - D. Beavis (Interim Officer)
  - M. White (Liaison)

- **DYB Safety Office**
  - Y.Q. Ma (Interim Officer)

- **Civil Construction**
  - H.Y. Zhang

- **Integration Office**
  - R. Brown
  - H.L. Zhuang

- **AD (Co-L2s)**
  - J. Cao
  - K. Heeger

- **Muon (Co-L2s)**
  - L. Littenberg
  - C.G. Yang

- **Calibration (Co-L2s)**
  - B. McKeown
  - J. Leung

- **Electronics (Co-L2s)**
  - X.N. Li
  - C. White

- **Offline (Co-L2s)**
  - J. Cao
  - C. Tull

- **I & T (Co-L2s)**
  - R. Brown
  - H.L. Zhuang
## US Cost Estimate

### Daya Bay Project Cost Estimate, FY07 US$

<table>
<thead>
<tr>
<th>WBS</th>
<th>Description</th>
<th>Base</th>
<th>% Cont</th>
<th>Contingency</th>
<th>Total</th>
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<tbody>
<tr>
<td>1</td>
<td>Antineutrino Detectors</td>
<td>8,455,791</td>
<td>36%</td>
<td>3,049,858</td>
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<td>1</td>
<td>Muon System</td>
<td>3,700,295</td>
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<td>806,326</td>
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<td>Calibration &amp; Monitoring</td>
<td>1,999,967</td>
<td>22%</td>
<td>428,733</td>
<td>2,428,700</td>
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<td>1</td>
<td>Electronics &amp; Online</td>
<td>212,876</td>
<td>12%</td>
<td>26,561</td>
<td>239,437</td>
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<tr>
<td>1</td>
<td>Offline</td>
<td>1,364,574</td>
<td>19%</td>
<td>252,969</td>
<td>1,617,543</td>
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<td>1</td>
<td>Conventional Construction &amp; Equip (PRC)</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>1</td>
<td>Installation Planning &amp; Support</td>
<td>1,961,186</td>
<td>19%</td>
<td>374,018</td>
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<td>System Integration</td>
<td>1,027,593</td>
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<td>203,363</td>
<td>1,230,956</td>
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<td>1</td>
<td>Project Management</td>
<td>1,766,037</td>
<td>8%</td>
<td>132,975</td>
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**Management Reserve (TEC)**

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<th>Total</th>
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<td>Subtotal (TEC)</td>
<td>20,428,318</td>
<td>30.0%</td>
<td>6,128,495</td>
<td>26,556,814</td>
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<td>1 10</td>
<td>3,570,809</td>
<td>5%</td>
<td>178,540</td>
<td>3,749,350</td>
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</table>

**Total Project Costs (TPC)**

<table>
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<th></th>
<th>Base</th>
<th>% Cont</th>
<th>Contingency</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td>23,999,128</td>
<td>26.3%</td>
<td>6,307,036</td>
<td>30,306,163</td>
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</tbody>
</table>

=> People's Republic of China Project Scope

$31.6M at-year
Major Milestone Summary

- Initial Chinese Funding Secured.............................. Apr-Aug 06
- **CD-1 Review passed**.................................................. Apr 07
- Start Tunnel Construction........................................... July 07
- **CD-2/3a Approval**.................................................... Nov 07
- PMT Contract Let......................................................... Nov 07
- **CD-3b Approval**....................................................... Mar 08
- AD Hardware in SAB (starting assembly).................... Jul 08
- Beneficial Occupancy of DB Near Hall...................... Sept 08
- 1st AD in Filling Hall.................................................. Nov-Dec 08
- DB Near Site Ready to take data............................... May 09
- Beneficial Occupancy of LA Near & Far Hall............. Apr & Jul 09
- **CD-4a Approval**....................................................... Nov 09
- All Near & Far Sites Ready to Take Data................. Apr 10
- **CD-4b Approval**....................................................... Sept 10
BNL DB Activity in 2006

- Joined collaboration in February 2006
- Led (co-led) task forces:
  - Simulations: David Jaffe
  - Liquid Scintillator: Dick Hahn
  - Muon Veto: Laurie Littenberg
  - Antineutrino Detector: Steve Kettell
- Lead role in preparation for the DOE Physics Review.
  - BNL hosted the Director's Review.
- Proposal (DOE Physics Review):
  - Leadership in drafting the Trigger/DAQ section
  - Leadership of the Muon System section.
  - Lead role in the coordination and drafting of the Installation, Operations and Project Development chapters and LS section.
  - Lead role in editing and coordinating the Proposal.
- Coordination of the US effort on the muon system and LS.
- Coordination of the US design integration effort.
- Lead role in drafting the successful US FY06 R&D proposal.
Activity at BNL in 2007

- BNL scientists have key roles in the Daya Bay Project:
  - Chief Scientist: Steve Kettell
  - Chief Engineer: Ralph Brown
  - Muon System L2 Manager: Laurie Littenberg
  - Installation and Integration L2 Managers: Ralph Brown
  - Liquid Scintillator L3 Manager: Minfang Yeh
  - Analysis and Simulation Software L3 Manager: David Jaffe
  - Co-leader of International Simulation effort: David Jaffe
  - Co-leader of International Liquid Scintillator Task Force: Dick Hahn

- CDR:
  - Chair of the Editorial Board and Editor-in-Chief: Steve Kettell
  - Members of the Editorial Board: David Jaffe and Laurie Littenberg
  - Technical advisor to the Editorial Board: Brett Viren
  - Lead Authors of 8 chapters: Steve Kettell, Laurie Littenberg, Ralph Brown.

- BNL is playing a lead role, along with LBNL and IHEP in the engineering design and integration, including the Civil Design specification.
- BNL is leading the effort to develop an installation plan
- BNL is playing a lead role in developing a Daya Bay safety plan.
Daya Bay staff at BNL

- BNL Scientific Staff:
  - Physics: 8 people (1 postdoc on LDRD, 1 engineer on DB R&D, 6 scientists on HEP base). Two more scientists involved and planning to join collaboration (supported on NP base). Two additional scientists with minimal involvement (one retired and one on HEP base).
  - Chemistry: 3 people (2 scientists almost supported on base NP, one postdoc supported on LDRD)
  - CAD: 1 person (scientist supported on NP base)
  - Total count of ~14

- FTE count:
  - FY07: 6.4 (3.4 Physics, 2.7 Chemistry, 0.3 CAD. Includes 2 LDRD supported postdocs)
  - FY08R: 7.8 (4.7 Physics assuming postdoc is replaced, 2.7 Chemistry assuming LDRD extension, 0.5 CAD) May add ~1.2 FTE in Physics supported on NP base.
**Gd Liquid Scintillator (WBS 1.1.3)**

(Chemistry Department)

**Gd-LS: A joint US-PRC-Russia activity**

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement &amp; Justification</th>
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</thead>
<tbody>
<tr>
<td>long-term chemical stability of Gd-LS</td>
<td>&gt; 3-5 years</td>
</tr>
<tr>
<td>high optical transparency for oil, LS and Gd-LS</td>
<td>&gt; 10 m</td>
</tr>
<tr>
<td>high photon production for Gd-LS</td>
<td></td>
</tr>
<tr>
<td>ultra-low impurity content</td>
<td>&lt; 10^{-12} g/g</td>
</tr>
<tr>
<td>C/H ratio determination</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>homogeneous distribution of Gd in LS</td>
<td>- thoroughly dissolving and mixing Gd in LS</td>
</tr>
<tr>
<td>chemical identity of oil, LS and Gd-LS between each detector module</td>
<td>- single-batch liquid storage for each phase before filling</td>
</tr>
</tbody>
</table>

![BNL Gd-LS samples](image1)

![BNL Solvent Extraction](image2)

![Graph](image3)

Fig. 6.23. The UV absorption values of BNL Gd-LS samples at 430 nm as a function of time.
Transporter/Cranes (WBS 1.7)

Studies of acceleration

40-ton Bridge Crane

Automatic Guided Vehicle

Transporter
Summary

• The measurement of $\theta_{13}$ at Daya Bay is a key part of the US HEP program
• This measurement is important in its own right and to plan future experiments to search for CP violation in neutrinos
  → All sites ready to take data 4/10. Measurement by ~2014
• BNL is playing a key role in this experiment and this Project
  • 7 scientists and 1 engineer from Physics
  • 3 scientists from Chemistry
  • 1 scientist from C-AD
  • additional admin and technical support
• Effort has grown from E949/RSVP transfer and BNL LDRD support (plus long term Chemistry involvement – 2004)
• Concerns:
  • There is concern whether we can get a 3-year Project funding profile
  • Concern over NP base support of LS effort
  • Need 1 postdoc (and travel) to replace existing staff!