Neutrinos and Dark Matter

Precision Measurements of Reactor Neutrinos and Search for Dark Matter at the South Pole

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NIST, Oct 17, 2011
Why neutrinos?
Neutrinos and photons are the most abundant particles in the Universe.
Neutrinos and Mass

$\nu_e \nu_\mu \nu_\tau$

PDG 2000 + SNO + SK

$\nu_3 < \nu_1 < \nu_2 < \nu_3$

neutrinos

charged leptons

quarks

“why is the neutrino mass so small?”

energy

mass
Neutrinos and the Structure of the Universe

“neutrinos and their mass have influenced the large and small-scale structure of the Universe”
Neutrinos and Baryon Asymmetry

Sakharov, 1967

1. baryon number violation
2. violation of C and CP
3. departure from thermal equilibrium

“neutrinos might explain the matter-antimatter asymmetry”
Heavy Elements: 0.03%
Ghostly Neutrinos: \( \sim 0.3\% \)
Dark Energy: 70%
Dark Matter: 25%
Matter in the Universe:
Free Hydrogen and Helium: 4%
Stars: 0.5%
\[ \sum m_\nu < \Omega_\nu < 0.015 \]
Now and 13.7 billion years ago

Now
- Atoms: 4.6%
- Dark Energy: 72%
- Dark Matter: 23%

13.7 billion years ago
- Atoms: 12%
- Neutrinos: 10%
- Photons: 15%
- Dark Matter: 63%

13.7 billion years
- 380,000 years old

1st Stars
- About 400 million yrs.

Big Bang Expansion
- 13.7 billion years
Elementary Particles in the Universe

Neutrinos and photons are the most abundant particles in the Universe.

There are 0.3GeV/cm³ of galactic Dark Matter.

We pass through this matter at 220km/s.

The Particle Universe

- photons
- neutrinos

330 neutrinos per cm³.
Neutrinos, Dark Matter, and the Universe

very early universe | big bang nucleosynthesis | CMB | late time structure formation

matter-antimatter ratio | CMB | large-scale structure
Neutrino Physics at Reactors

**Next** - Discovery and precision measurement of $\theta_{13}$

- **2008** - Precision measurement of $\Delta m_{12}^2$. Evidence for oscillation
- **2003** - First observation of reactor antineutrino disappearance

- **1995** - Nobel Prize to Fred Reines at UC Irvine

- **1980s & 1990s** - Reactor neutrino flux measurements in U.S. and Europe

- **1956** - First observation of (anti)neutrinos

Past Reactor Experiments
- Hanford
- Savannah River
- ILL, France
- Bugey, France
- Rovno, Russia
- Goesgen, Switzerland
- Krasnoyark, Russia
- Palo Verde
- Chooz, France

55 years of liquid scintillator detectors a story of varying baselines...
Discovery of the Neutrino

1956 - “Observation of the Free Antineutrino” by Reines and Cowan

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Reactor Antineutrinos

\( \bar{\nu}_e \) from n-rich fission products

\(~ 200 \text{ MeV per fission} \)
\(~ 6 \bar{\nu}_e \text{ per fission} \)
\(~ 2 \times 10^{20} \bar{\nu}_e / \text{GW}_{\text{th}} \cdot \text{sec} \)

mean energy of \( \bar{\nu}_e \): 3.6 MeV

only disappearance experiments possible

cross-section accurate to +/-0.2%
Oscillation Experiments with Reactors

Looking for non-\(1/r^2\) behavior of \(\overline{v}_e\) interaction rate

\[
P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_{\nu}} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_{\nu}} \right)
\]

L/E oscillation effect provides measurement of \(\Delta m^2\) amplitude of oscillation provides measurement of \(\theta\)

for 3 active neutrinos, can study oscillation with two different oscillation length scales: \(\Delta m_{12}^2, \Delta m_{13}^2\)

\[
\Delta m_{12}^2 \sim 8 \times 10^{-5} \text{ eV}^2 \\
\Delta m_{13}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2
\]

Only disappearance experiments are possible since mean antineutrino energy is 3.6 MeV.
Oscillation Searches with Reactor Antineutrinos

1980-1990s
Chooz
8.5GW power
1 km baseline

8.5GW power
1 km baseline

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

absolute measurement with 1 detector, $\sigma_{\text{det}} \sim 2.7\%$

time with reactors off critical for background studies

No evidence for oscillation
Measuring Reactor Antineutrinos with KamLAND

Reactors in Japan

Kashiwazaki

Takahama

Ohi

55 reactors

$^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} = 0.570 : 0.078 : 0.0295 : 0.057$

KamLAND

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

through inverse $\beta$-decay

reactor $\bar{\nu}$ flux at KamLAND

$\sim 6 \times 10^6$/cm$^2$/sec
KamLAND 2003: Evidence for Reactor $\bar{\nu}_e$ Disappearance

Reactor Neutrino Physics 1956-2003


- Observed $\bar{\nu}_e$: 54 events
- No-Oscillation: 86.8 ± 5.6 events
- Background: 1 ± 1 events
- Livetime: 162.1 ton-yr

mean, flux-weighted reactor distance ~ 180km
KamLAND 2010: Precision Measurement of Oscillation

Prompt Energy Spectrum

L/E Dependence

KamLAND, Phys.Rev. D83 (2011) 052002

reactor phase of KamLAND is completed
KamLAND → KamLAND-Zen in July 2011
continues to record antineutrino data
KamLAND 2010: Precision Measurement of Oscillation

Precision Measurement of $\Delta m^2_{21}$

KamLAND averaged baseline $\approx 180$km
not optimized for $\theta_{12}$ oscillation effect

KamLAND, Phys.Rev. D83 (2011) 052002
Neutrino Oscillation

Mixing Angles & Mass Splittings

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

\[ U_{\text{MN}} \text{ Matrix} \]
Maki, Nakagawa, Sakata, Pontecorvo

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

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

Schwetz et al
Neutrino Oscillation

Mixing Angles

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

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

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

atmospheric, K2K  \quad \text{reactor and accelerator}  \quad \text{SNO, solar SK, KamLAND}  \quad 0\nu\beta\beta

\[
\begin{align*}
\sin^2 \theta_{23} &= 0.50^{+0.07}_{-0.06} \\
\sin^2 \theta_{13} &= 0.013^{+0.013}_{-0.009} \\
\sin^2 \theta_{12} &= 0.318^{+0.019}_{-0.016}
\end{align*}
\]

maximal?  \quad \text{small? zero?}  \quad \text{large, but not maximal!}

because of small \(\sin^2 2\theta_{13}\), solar & atmospheric \(\nu\) oscillations almost decouple

Karsten Heeger, Univ. of Wisconsin  \quad NIST, October 17, 2011
Global Fits and $\theta_{13}$


Lisi et al, arXiv:1106.6028
Measuring $\theta_{13}$ with Reactor Experiments

Near-Far Concept

$\bar{\nu}_e$ \hspace{2cm} $\bar{\nu}_{e,x}$

distance $L \sim 1.5$ km

$\sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$

Energy (MeV)

$N_{0.85 e}/N_{0.85 \text{no-osc}}$

Baseline (km)

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \equiv 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$
Measuring $\theta_{13}$ with Reactor Experiments

Near-Far Concept

- $\bar{\nu}_e$
- $\bar{\nu}_{e,x}$

Distance $L \sim 1.5$ km

- Near
- Far

A clean measurement of $\theta_{13}$ at optimized distances without parameter degeneracies

Karsten Heeger, Univ. of Wisconsin
World of Reactor $\theta_{13}$ Neutrino Experiments

- Diablo Canyon, USA
- Braidwood, USA
- Angra, Brazil
- Chooz, France
- Krasnoyarsk, Russia
- Kashiwazaki, Japan
- RENO, Korea
- Daya Bay, China

Daya Bay, Double Chooz, and Reno
- international collaborations
- taking data
Daya Bay - A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW$_{th}$ (6 x 2.95 GW$_{th}$)
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays
Daya Bay, China
http://dayawane.ihep.ac.cn/

- total of 8 movable detectors
- multiple detectors per site to cross-check efficiency

RPCs
PMTs
water pool
muon veto system

experimental hall

Far Site (4 detectors)
Ling Ao (3 detectors)

antineutrino detectors (AD)
Daya Bay Antineutrino Detectors

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut

- target mass: 20t per detector
- detector mass: ~ 110t
- photosensors: 192 PMTs
- energy resolution: 12%/$\sqrt{E}$

νₑ + p → e⁺ + n

Gd-doped liquid scintillator

steel tank

acrylic tanks

photomultipliers

calibration system (LED, $^{68}$Ge, AmC-Co)
Antineutrino Detector Assembly

detector assembly in pairs
AD1-4 assembled and filled
AD5,6 assembly in progress
Antineutrino Detector During Pool Filling

Detector 1

Detector 2

in air

in water
Antineutrino Detector Performance - First Look

AmC-\(^{60}\)Co Source at Center of Antineutrino Detector

neutron-capture energy spectrum

\begin{align*}
\text{Preliminary}
\end{align*}

neutron capture time

\begin{align*}
\text{Preliminary}
\end{align*}

Daya Bay near detectors are taking data!

AD1 : \( \tau_{\text{cap}} = 28.40 \pm 0.40 \ \mu s \)

AD2 : \( \tau_{\text{cap}} = 28.21 \pm 0.35 \ \mu s \)
Daya Bay Systematic Uncertainties

Detector-Related Uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Chooz (absolute)</th>
<th>Daya Bay (relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline</td>
</tr>
<tr>
<td># protons</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cuts</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Position cuts</td>
<td>0.32</td>
<td>0.0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>H/Gd ratio</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Trigger</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Live time</td>
<td>0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total detector-related uncertainty</td>
<td>1.7%</td>
<td>0.38%</td>
</tr>
</tbody>
</table>

O(0.2-0.3%) precision for relative measurement between near and far detectors

Key Features
- Near-Far comparison, functionally identical detectors
- Redundant muon tagging
- Option to swap detectors

estimated target mass error < 0.03% from filling

Ref: Daya Bay TDR
Daya Bay Status and Prospects

Daya Bay has completed 4 out of 8 antineutrino detectors

- AD1,2 installed and taking data
- AD3,4 assembled and filled
- AD5,6 assembly in progress
- AD7,8 completion in Spring 2012

Daya Bay is most sensitive reactor $\theta_{13}$ experiment under construction.

August 2011 data taking with Daya Bay near site
Summer 2012 start data taking with full experiment
Measuring $\theta_{13}$: A Possible Scenario

Upper limit at 90% CL in case of no signal

- First hint of $\theta_{13}$ by Double Chooz, Reno, and T2K possible if $\theta_{13}$ large
- Precision measurement to $\sin^2 2\theta_{13} < 0.01$ by Daya Bay

Mezzetto et al
arXive/1003.5800v1
Neutrinos and photons are the most abundant particles in the Universe.

There are 0.3GeV/cm³ of galactic Dark Matter.

We pass through this matter at 220km/s.
Dark Matter

1975
Vera Rubin found that rotation curves are flat

95% of the matter in galaxies is unknown dark matter
Galactic Halo
Techniques for Detecting Dark Matter

- **Indirect detection**  
  (IceCube, etc.)  
  – observe products of WIMP annihilation/decay in terrestrial or space based detectors

- **Direct detection**  
  (CDMS, XENON, DEEP, LUX, DAMA, etc.)  
  – observe WIMPS through scattering with matter in terrestrial detectors

- **Colliders**  
  – produce WIMPs directly at the LHC
Dark Matter Bounds from Terrestrial Experiments

Spin-Independent

Spin-Dependent

One, ...maybe two, maybe three signals?

One claim for discovery: DAMA
DAMA

- Gran Sasso National Laboratory, Italy under ~3800 m.w.e of rock.

- DAMA/NaI consisted of ~100 kg of NaI
- DAMA/LIBRA ~250kg
  - 25 crystals (10 x 10 x 25 cm$^3$, 9.7 kg)

- Look for scintillation in NaI with two PMTs, 5 - 7 p.e./keV
- background: ~1-2 events/kg/d/keV
- $E_{\text{threshold}}$: 2 keV$_e$ (25 keV$_r$)
Hints of Dark Matter in Direct Experiments?

Some tantalizing signals...

- Observation by DAMA (8.9σ).
- Recent results from CoGeNT show events at low energies and annual modulation (2.8σ).
- Excess events in CDMS (but no observation in their low-energy analysis), null results from XENON 100.

What could it be...?

- Background? Detector effects?
- Light WIMPs? Non-standard physics?
Possible Explanations for Annual Modulation

- **Environmental Effects/Backgrounds**
  - Ambient temperature variation
  - Muon flux depend on temperature/pressure in the upper atmosphere
  - Spallation neutrons from muons interaction in rock
  - Radon diffusion from rocks may be varying with time
  - Detector and lab maintenance timing

- **Detector Effects**
  - Quenching factor
  - Channeling
  - Xenon scintillation function

- ** Astrophysical Uncertainties?**
  - $f(v) \ ? \ v_{\text{esc}} \ ? \ v_0 \ ? \ \text{co-rotating?}$

Many of these factors tend to have periodicity of 1 year

Repeat experiment in different environment. Look for annual modulation with NaI(Tl) in Southern Hemisphere.
Requirements for Testing DAMA Annual Modulation

- **Environment/location with different systematics**
  - Site with different systematics and backgrounds than what might mimic the observed annual modulation signal
  - Southern Hemisphere?

- **Low background rates (< 1 event/kg/keV/day)**
  - Use clean detectors and surrounding materials. Limited by intrinsic NaI(Tl) background.
  - Deep underground site with muon shielding

- **> 250kg of NaI(Tl) detectors**
  - same or larger size than DAMA to collect sufficient statistics

- **Long-term stability in operation (> 2 years)**
  - would like to see at least 2 annual modulations if signal is seen
Going to the South Pole
Astrophysics at the South Pole

South Pole

runway

IceCube

IceCube Control Lab

Amundsen-Scott South Pole Station

AMANDA

SPT, BICEP II
Amundsen-Scott South Pole Station

runway

IceCube

South Pole

AMANDA

our laboratory
Dark Matter Annual Modulation Search at South Pole

- **Annual Modulation Signal**
  - Phase of the dark matter modulation is the same.
  - Opposite seasonal modulation, e.g. muon rate (max in December).

- **Overburden with clean, radiopure ice (> 2500 m.w.e.)**
  - Many sources of backgrounds either non-existent or different from other underground sites.
  - Clean ice → Very little uranium/thorium. No radon.
  - Ice is a great neutron moderator.
  - Ice as an insulator → No temperature modulation.

- **Existing infrastructure**
  - NSF-run Amundsen-Scott South Pole Station
  - Ice drilling down to 2500 m developed by IceCube
  - Muon rates well understood by IceCube/DeepCore
  - Infrastructure for construction, signal readout, and remote operation
Muon Rate Seasonal Modulation

Gran Sasso

• LVD:
  Selvi, Proc. 31st ICRC.

South Pole

• Opposite Muon modulation at the South Pole:
  Tilav, Proc. 31st ICRC. (2009)
Starting a Dark Matter Experiment at the Pole

Window of Opportunity

- IceCube construction finished in Dec. 2010
- Currently infrastructure and drill for deep deployment of instrumentation at South Pole

Challenges

- Extreme environment
- Detector will be inaccessible once deployed.
- But...
  - NaI and CsI detectors have been launched into space (e.g. EGRET, Fermi LAT)
DM-Ice: A Dark Matter Experiment at the Pole

First step: A 17 kg Prototype

Detectors

- Two 8.5 kg NaI detectors from NAIAD

Goals

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

Installed Dec. 2010
DM-Ice 17kg Prototype

- Stainless Steel Pressure Vessel
- NAIAD NaI Crystal (8.5 kg)
- quartz light guides (2)
- 2 IceCube mainboards + HV control boards
- 5" ETL PMTs from NAIAD (2)
- PTFE light reflectors (2)
- ~1.0 m
- ~36 cm (14”)
- 7 m extension cable
- 35 m extension cable
- attached to end of IceCube strings
On-Ice Detector Storage and Testing
Hot Water Drilling into the Ice
Hot Water Drilling into the Ice

Firm Drill

Deep Drill
Tower Operations Site
TOS Delivers Water to Hole
Seasonal Equipment Site
Drill Camp
Drilling Water-Filled Deep Holes

• **Hole filled with water**
  – empty hole deeper than ~400 m would be closed by the pressure from the surrounding ice.
  – pressure at the bottom of on IceCube hole is ~240 atm or 3500 psi
  – freeze instrumentation into the ice
    • Good optical coupling to the ice (for PMTs)
    • Support the weight of the cable and DOMs
    • Fixed position

• **Hole needs to be over 17 inch (45 cm) in diameter for 24 hours to allow enough time for deployment.**
  – “lifetime” of hole ~ 24-36 hrs.
  – hole is about 24 inch (60 cm) after completion of drilling. It slowly freezes and shrinks

• **Hot water drilling makes water-filled holes quickly**
IceCube Counting Laboratory (ICL)
DM-Ice Concept

~2500m

local muon veto in ice

~250 kg NaI detector array in pressure vessel

local muon veto in ice

250kg NaI Detector Array Deep in the Ice

runway

Amundsen-Scott South Pole Station

IceCube

South Pole

IceCube

~250 kg NaI Detector Array Deep in the Ice

local muon veto in ice

~250 kg NaI detector array in pressure vessel

local muon veto in ice
DM-Ice Concept

- ~ 2500 m deep in the ice
- Local muon veto
- Stainless steel pressure vessel
  - Copper shielding if needed
- Electronics & pulse digitization in the vessel
- Location: near the center of IceCube for additional veto

x2 or 3

~150 cm

~65 cm
DM-Ice: A Dark Matter Experiment at the Pole

Summary&Conclusions

- We have an opportunity for a unique annual modulation experiment in Southern Hemisphere.
- Backgrounds and systematics very different from any other underground location.
- Two prototype NaI(Tl) detectors (17kg) installed and operating in the South Pole ice since Dec 2010.
- Full-scale (250-500kg) experiment currently under design.
- An unambiguous discovery of DM requires signal in multiple experiments with different targets.

see arXiv:1106.1156
Thank you!
DM-Ice Collaboration

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Lauren Hsu

University of Stockholm
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Charles Duba, Eric Mohrmann

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