Search for Neutrino Oscillations at the South Pole

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ICRR Seminar – University of Tokyo
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Outline

- Motivation
- The IceCube Neutrino Observatory
- Neutrino Oscillation
- Indirect Search for Dark Matter
- The Deep Core sub-detector
- Outlook – Deep Core Physics
- Conclusions
Motivation
Some Questions

What are the sources of the cosmic rays?

What are the most energetic phenomena in the Universe?

What is the nature of the acceleration mechanism to create these energetic events?

What is the Universe made of?
- What is Dark Matter?
Protons interact in “target area” to produce pions:
\[ p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma \gamma \]
\[ \rightarrow \pi^\pm \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau \]
(1:2:0) (1:1:1)

Neutral pions → Photons
Charged pions → Neutrinos
Oscillations result in 1:1:1 flavor ratio at detector

Source Candidates:
- Active Galactic Nuclei
- Supernova Remnants
- Gamma Ray Bursts
- ...


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Astro Messengers

Neutrinos
- Unobscured view into depth of space
- Point back to their sources
- Cover entire energy spectrum

Protons
- bent below 10 EeV
- above 50 EeV GZK cut-off

Photons
- scattered/absorbed above 50 TeV

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The IceCube Neutrino Telescope

Photo: Cynthia Chiang
Muon Neutrino

- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- $O\ (\text{km})$ muons from $\nu_\mu$
- $O\ (10\text{m})$ cascades from $\nu_e, \nu_\tau, \text{NC}$

Array of optical sensors capture the light

Cherenkov Radiation

A Generic Optical Neutrino Telescope
**IceTop (~50% complete)**
- Surface air shower array
- 300TeV threshold

**IceCube InIce (~50% complete)**
- 80 Strings with 60 DOMs each
- Hexagonal pattern with an interstring distance of 125m
- Vertical DOM spacing of 17m
- Optimized for TeV range

**Deep Core (construction starting now)**
- 6 Strings with 60 High Quantum Efficiency DOMs (vert. spacing 7m)
- Low Energy extension (20-100GeV)
- First string will be deployed end of this year

IceCube will instrument a volume of one cubic kilometer of Antarctic ice by 2011
Digital Optical Module (DOM)

- 10 inch Hamamatsu PMT (R-7081-02)
- Measure individual photon arrival time:
  - 2 ping-ponged four-channel Analog Transient Waveform Digitizers:
    - 128 samples (400 ns max range)
    - ~3.3 ns bin
    - 400 pe / 15 ns
  - fast Analog-to-Digital Converter:
    - 40 MHz
    - 6.4 μs range

- Dark Noise rate ~ 700 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Signal digitized in the ice

Example: Digitized Waveform
IceCube Deployment

2004–2005
1 string deployed
First data
astro-ph/0604450
IceCube Deployment

2004–2005
1 string deployed
First data
astro-ph/0604450

2005–2006
8 string deployed
IceCube Deployment

2004–2005
1 string deployed
First data
astro-ph/0604450

2005–2006
8 string deployed

2006–2007
13 strings deployed
IceCube Deployment

- **2004-2005**: 1 string deployed
  - First data
  - astro-ph/0604450
- **2005-2006**: 8 string deployed
- **2006-2007**: 13 strings deployed
- **2007-2008**: 18 strings deployed

**Total 40 Strings deployed**
(50% of full detector installed)

Completion by 2011
IceCube Deployment

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(50% of full detector installed)
Completion by 2011
IceCube Deployment

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(50 % of full detector installed)
Completion by 2011

This season plan to deploy 16 strings (incl. 1 deep core string)

2004–2005
1 string deployed
First data
astro-ph/0604450

2005–2006
8 string deployed

2006–2007
13 strings deployed

2007–2008
18 strings deployed
13 Strings Deployed so far from 12/06/08

Night-shift deployment team with the last DOM of String 27, December 8, 2008
IceCube Deployment

Total 40 Strings deployed

2004–2005
1 string deployed
First data
astro-ph/0604450

2005–2006
8 string deployed

2006–2007
13 strings deployed

2007–2008
18 strings deployed

 Completion by 2011
This season plan to deploy 16 strings (incl. 1 deep core string)
Muons produced in air showers are ideal calibration beam for the detector:

- Test track reconstruction
- Verify detector timing and stability

Timing stability ~ 2ns

Problem: We cannot switch off the “calibration beam”
Atmospheric Neutrinos

$\phi \sim E^{-3.7}$

<table>
<thead>
<tr>
<th>Strings</th>
<th>$\mu$ rate</th>
<th>$\nu$ rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMANDA</td>
<td>80 Hz</td>
<td>4.8 / day</td>
</tr>
<tr>
<td>IC22</td>
<td>550 Hz</td>
<td>28 / day</td>
</tr>
<tr>
<td>IC40*</td>
<td>1200 Hz</td>
<td>110 / day</td>
</tr>
<tr>
<td>IC80*</td>
<td>1650 Hz</td>
<td>220 / day</td>
</tr>
</tbody>
</table>

AMANDA: $O(10^9)$ events/yr
IceCube: $O(10^{10})$ events/yr

IceCube-22 Data vs. Monte Carlo Simulation Data

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## Neutrino Event Identification

### Tracks

<table>
<thead>
<tr>
<th></th>
<th>IceCube</th>
<th>AMANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td>2 ns</td>
<td>5-7 ns</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>0.3 - 0.4</td>
<td>0.3 - 0.4</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>$2\pi$</td>
<td>$2\pi$</td>
</tr>
<tr>
<td><strong>Noise Rate</strong></td>
<td>low</td>
<td></td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>$&lt;1^\circ$</td>
<td>$\sim 1.5-2.$</td>
</tr>
</tbody>
</table>

### Cascades

<table>
<thead>
<tr>
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<th>AMANDA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td>2 ns</td>
<td>5-7 ns</td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>$4\pi$</td>
<td>$4\pi$</td>
</tr>
<tr>
<td><strong>Noise Rate</strong></td>
<td>low</td>
<td></td>
</tr>
<tr>
<td><strong>Angular resolution</strong></td>
<td>$30^\circ$</td>
<td>$\sim 30-40^\circ$</td>
</tr>
</tbody>
</table>
Neutrino Oscillations & “Low” Energy Physics

\[ |\Delta m^2| \ (10^{-3} \text{ eV}^2) \]

\[ \sin^2(2\theta) \]

- MINOS best oscillation fit
- MINOS 90%
- MINOS 68%
- Super-K 90%
- Super-K L/E 90%
- MINOS 2006 90%
- K2K 90%
Atmospheric Oscillations

As $\Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}}$

Atm. oscillations can be described with the 2 flavor assumption

$\nu_\tau \leftrightarrow \nu_\mu$

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_{\nu}} \right)$$

---

**Zenith Angle Distributions (SK-I + SK-II)**

Livetime
- SK-I 1489d (FCPC)
- SK-II 804d (FCPC)
  828d (Upmu)

All distributions agree with oscillated expectations

---

**Novel Searches for DM 17/11/2008**

- SK-I 1646d (Upmu)
- SK-II 804d (FCPC)
  828d (Upmu)
Motivations for muon neutrino oscillation measurements with IceCube

- Test oscillations at a different energy range ($E_{\nu_{\mu}} \sim 30-100$ GeV) than what is directly accessible by other experiments.

- Same analysis framework is used for the Earth WIMP search.

- Explore an energy region that has currently not been tested by any other analysis in IceCube.

- Open a new energy window. Especially important for low energy physics with Deep Core. Develop understanding of the interesting energy region now.

- Demonstrate detector understanding for IceCube in this new energy region.
The Basic Idea

Oscillation effects are significant for energies below about 100 GeV (assuming a baseline of the order of the diameter of the Earth)

Lowest energy threshold in IceCube is realized in vertical events
- IC22 ... Trigger threshold 8 DOMs hit
- IC40 ... New String trigger threshold 5 DOMs hit

Low energy muons have an energy loss of about $\Delta E \sim 1 \text{GeV}/5\text{m}$

$\mu_{\text{up}}/\mu_{\text{down}}$ could be used for normalization
difficult due to background contributions, “directionality” DOMs (face down)

Related idea discussed in Albuquerque and Smoot, PRD.64.053008
Directionality of track:
Compute time difference between DOMs and determine if it is up or down-going

\[ n\text{diff}_\text{up} = 3 \]
\[ n\text{diff}_\text{down} = 1 \]

\[ \text{directionality} = \frac{n\text{diff}_\text{up} - n\text{diff}_\text{down}}{(nch-1)} \]
Energy and zenith angle of muon neutrino events after described selection criteria

Cumulative Point spread function

Signal sample dominated by vertical up-going events

Hypothesis of up-going events

... but still factor of about 25 times more background than signal at this level
IceCube can probe oscillations with fully contained events in a different energy range than Super K

- Do not expect any deviations, but we have never really looked at this range

Super K
Analysis Strategy

Use small subset of data to cross-check if MC predictions agree with it:

3) Result on the small subset won’t be statistically significant for the signal to avoid any later bias

5) Especially important as we are looking for the first time at a new region of “MC” parameter space

6) Evaluate the entire dataset in final analysis

Use large sample of latest version background MC; only a limited background MC dataset was available at the time of the analysis for the cross-check
Main remaining background:

Vertically up-going muon neutrino faked by down-going atmospheric muons that have a stochastic (example Bremsstrahlung) produced next to a string and do not produce any hits in the adjacent strings, this is especially true for outer string, which have less of a veto volume around them.

How to get ride of these events?
- Light travels with c/n compared to c
- Inner strings are better isolated
Available background MC was statistically limited, hence define selection criteria on individual distribution which are not strongly correlated and reduce it as much as possible to regain a “pure” signal dataset

- Mean charge per DOM > 1.25 pe
- Total charge in first 500 ns >12 pe
- Inner strings only
- Directionality based on DOM pairs consistent with speed of light
- Veto events with hits in the top 5 DOMs

**Mean charge per DOM**

**Inner/Outer Strings**
Selection criteria optimized on simulation which agrees well with data.

Background can be rejected effectively, however available background sample was statistics limited (equiv. 1.45 days of livetime)

IC22 data subsample (12.8 days) (<5% of total data) was used as cross-check.

After final selection expected:
- **Signal (Muon Neutrinos):**
  - 1.81 events (no-osc)
  - 1.42 events (osc)
- **Background:**
  - 0.0 ± 20.3

Observed in data:
- 3 Events

In agreement with predictions

C.Rott, ICHEP08 (arXiv:0810.3698)
Initial IC22 results very promising
- Data and MC expectations agree
- Larger improved background MC dataset is now studied
- Systematic uncertainties and other effects being investigated
  - Neutrino flux uncertainty
  - Optical sensor efficiency
  - Ice effects (layers,...)
  - Kinematic smearing
  - Effect of tau
...

IC40 data is also becoming available now
Analysis method can be almost directly be transferred from IC22 to IC40

Estimated sensitivity to oscillation parameters using expected IC40 results
Improvements through Detector size

Year Strings (Inner)

<table>
<thead>
<tr>
<th>Year</th>
<th>Inner Strings</th>
<th>Outer Strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>2008</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>2009</td>
<td>56</td>
<td>27</td>
</tr>
</tbody>
</table>

Outer strings have high background

Almost factor of 3 more inner strings in IC40 compared to IC22 (they are in addition also better isolated)
Topological trigger allow to lower the energy threshold further compared to the default multiplicity 8 trigger.

Selects events based on a certain pattern present in the detector.

Beginning with IC40 data taking a string trigger has been added to IceCube’s trigger.

Detectable events were defined as events that have at least one hit in the detector.

**String Trigger:**
5 DOMs hit within a series of 7 DOMs within a time window of 1500ns.
IC40 Improvements Summary

- 3x more inner strings
- 2x more events due to string trigger
- 10% improvement in filter efficiency
- Increased detector uptime
- Access to lower energies due to string trigger
  - Oscillation effects more pronounced
    - expect x10 more stat. for IC40 compared to IC22
- Expect at least one order of magnitude more (candidate) signal events
- Further studies of these events will lead to a better understanding of low energy region and will benefit the analysis
IceCube probes a different energy region compared to other oscillation experiments

Expected results of $\chi^2$ test using the track length as energy estimator

IceCube probes a different energy region compared to other oscillation experiments

(m = 2)

Expect in the IC40 dataset to see oscillation effects

C.Rott, ICHEP08 (arXiv:0810.3698)
IC22 and IC40 analysis both in progress now

Expect results at ICRC 09

IC40 data is expected to be large enough to show first signs of observable oscillation effects

Oscillation analysis important test at low energy region, which is not well covered
Indirect Searches for Dark Matter
Solar WIMPs

The Sun sinks maximally 23° below the horizon at the south pole

Cosmic Rays: \( \mu, \gamma, \pi, \kappa, \ldots \)

\[ \tilde{\chi} \tilde{\chi} \rightarrow q \bar{q}, l \bar{l}, \ldots \rightarrow \nu_\mu \]

\( W^\pm, Z, H \) interactions hadronization

\[ \rightarrow c \bar{c}, b \bar{b}, t \bar{t}, t^+ t^-, W^\pm, Z^0, H^\pm H^0 \]
Solar WIMPs

[PRL in preparation]

Direct limits (very approx)

AMANDA

IceCube 22

Preliminary

Spin dependent scattering

Neutralino mass (GeV)

Neutrino flux from Sun (km$^2$ yr$^{-1}$)
Place 90% C.L. limit on muon flux from the center of the Earth

- AMANDA Earth Wimp analysis on-going
- IceCube Earth Wimp analysis on-going
- Understanding of low energy vertical tracks extremely important (relates closely to oscillation analysis)
Deep Core Strings

- 6 strings with high quantum efficiency PMTs, densely spaced
- 7 “standard” IceCube strings located in best ice (below 2100 m exceptionally clear)
- Interstring spacing 72m
- Uses high Quantum Efficiency PMTs, that have about 40% higher efficiency
- Located in the deep ice
- Lower atmospheric muon background
- Larger scattering length ~40m
Effective Veto against down-going muons from surrounding strings and DOMs above (~$10^5$ reduction in background)

Large veto region allows for $4\pi$ steradians (all sky) analysis

- Southern Sky
- Year around sun

**IceCube:**

\[ D_{\text{scatter}} = 20\text{m} < \frac{1}{2} D_{\text{interstring}} = 125\text{m}/2 \]

**Deep Core:**

\[ D_{\text{scatter}} = 40\text{m} \sim \frac{1}{2} D_{\text{interstring}} = 72\text{m}/2 \]

direct light

First Deep Core string this season (Jan 2009)
Southern Sky (Galactic Centre - Galactic plane)
Cascade direction and reconstructions
Atmospheric electron neutrino spectrum
Low energy atmospheric neutrinos
Oscillations
Neutrino Mass Hierarchy
Neutrino Tomography
Wimp improvements

...
• Transition probabilities \((1 - P_{e\rightarrow e})\)

Akhmedov, Maltoni & Smirnov, hep-ph/0612285
Matter effects enhance the oscillation probability for (anti-)neutrinos if the mass hierarchy is normal (inverted).

In the relevant energy range the anti-neutrino cross-section is smaller than that of neutrino by roughly a factor of 2.
### Dark Matter Searches

<table>
<thead>
<tr>
<th>Solar</th>
<th>Earth</th>
<th>Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background off-source on-source</td>
<td>Background simulations</td>
<td>Background off-source on-source</td>
</tr>
<tr>
<td>Muon neutrinos</td>
<td>Muon neutrinos</td>
<td><strong>Cascades</strong>, Muon neutrinos</td>
</tr>
<tr>
<td>Neutrino Flux, <strong>Scattering cross-section</strong></td>
<td>Neutrino Flux, ?</td>
<td>Neutrino Flux, <strong>Self-annihilation cross-section</strong></td>
</tr>
<tr>
<td>Excess</td>
<td>Excess</td>
<td><strong>Anisotropy</strong>, Spectrum</td>
</tr>
<tr>
<td><strong>IceCube</strong> ( + Deep Core)</td>
<td><strong>IceCube</strong> ( + Deep Core)</td>
<td><strong>DeepCore</strong> ( + IceCube)</td>
</tr>
</tbody>
</table>

January 9, 2009
Conclusions

- IceCube is taking data with the half completed detector
- This season plan to add at least 16 new strings
  - 13 have been deployed so far this season
  - 1 of the new strings will be a Deep Core String
- Deep Core will substantially enhance IceCube’s low energy sensitivity
- Already now in a special sub-class of events (vertical/close to a string) we can study low energy neutrino (<100GeV)
  - Muon Neutrino Disappearance should be observable in the IC40
- Physics Analyses in full swing now … Expect many new results for ICRC 2009
Backup Slides
Hottest spot found at r.a. 153º, dec. 11º
est. nSrcEvents = 7.7  est. gamma = 1.65
max. llhRatio = 13.4
est. pre-trial p-value: \(-\log_{10}(p): 6.14\) (4.8 sigma)

Post-trials p-value of analysis is \(\sim 1.34\%\) (2.2 sigma) ...