Light Propagation in the South Pole Ice

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From neutrino to DOM

Photons undergo scattering and absorption in ice

Modeling the light propagation in ice is critical to reconstructing the properties of IceCube events
IceCube Calibration Devices

Muons from cosmic ray-induced air showers

Dust logger (8 locations)

2 nitrogen laser “standard candles”

12 LED flashers aboard each DOM

One camera located at the bottom of a string near the center of IceCube (see talk by Per Olof Hulth, this session)
Flasher Measurements in IceCube

Flasher data collected in 2008 during IceCube construction
40 strings active

Received charge vs. time from flashing DOMs, collected by neighboring DOMs
Received charge vs. depth

Depth increases with DOM number from 1450 m (DOM 1) to 2450 m (DOM 60)

Received charge is plotted for flasher at the same depth as the receiver

Strong depth-dependent variations => depth-dependent scattering and absorption due to layers of dust in the ice
Simulation

- Direct photon propagation with Photon Propagation Code (PPC)
- Geometric scattering coefficient $b$: distance between successive scatters is $1/b$
- Effective scattering coefficient $b_e$

$$b_e = b \cdot (1 - \langle \cos \theta \rangle) \quad \theta \text{ is the angle between scatters}$$

- Absorption coefficient $a$: distance travelled by photon before absorption is $1/a$
- Divide detector into 100 10-m layers in depth, fit to $a$ and $b_e$ in all layers (200 parameters)
- Simulate many values of $a$ and $b_e$, find best fit to data using likelihood method
Scattering Function

Use linear combination of simplified Liu and Henyey-Greenstein models to approximate Mie Scattering

\[ g = \langle \cos \theta \rangle = 0.9 \]

**Simplified Liu:**

\[ p(\cos \theta) \sim (1 + \cos \theta)^\alpha, \quad \text{with} \quad \alpha = \frac{2g}{1 - g} \]

**Henyey-Greenstein:**

\[ p(\cos \theta) = \frac{1}{2} \left[ 1 - \frac{1 - g^2}{1 + g^2 - 2g \cdot \cos \theta} \right]^{3/2} \]

**Mie:**

Describes scattering on acid, mineral, salt, and soot with concentrations and radii at South Pole
Melted and re-frozen “hole ice” introduces additional scattering. Effective scattering length of 50cm in the hole (under study) modeled as a change in the effective angular sensitivity of the DOM.
Results: SPICE Mie

SPICE = South Pole Ice model

Absorption  Scattering

Gray band: range allowed by uncertainties: ±10%

Likelihood functions using charge information only (left) and both charge and time information (right)
Comparison with Dust Log Data, Tilt

Dust log data shows that dust layers in ice are tilted.

Comparison of simulation to 2012 flasher data over 200 m from string 63, shows strong effect from dust layer tilt.

Effective scattering from dust log agrees with value from flashers.
Delta T from Muons

Comparison of difference in arrival times at neighboring DOMs on a string
Anisotropy in Scattering

Ratio of simulated (SPICE Mie) charge to data on strings surrounding the flashing string

Maxima of ratio histograms vs. azimuth
Anisotropy

16.0% per 100 m

amplitude of variation

distance [m]
Ice Model with Anisotropy: SPICE Lea

Absorption

Scattering

D. Chirkin, ICRC 2013
Model error improvement

SPICE Mie flasher data/simulation comparison

SPICE Lea comparison
Comparison with Muon Data

Data
SPICE Mie simulation

Ratio of data to simulation

Direction of maximum charge agrees with data from flashers
Summary

- Ice at the South Pole has complex depth- and x-y-dependent variations
- Model fit to flasher data using direct photon propagation shows good agreement with data
- Many more studies are ongoing
  - Using flasher data at multiple locations in the detector
  - Using multi-wavelength flasher data
  - Direct simulation of the hole ice