A study of neutrino absorption radiography of the Earth with AMANDA-II neutrino data

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Using the AMANDA-II neutrino data collected during the period from 2000 to 2006, we performed neutrino absorption radiography for studying density of the Earth. Two absorption curves obtained from horizontal events and vertically upward going events are compared as a function of neutrino energy threshold. The results are consistent with numerical simulations within error bars.

Key words: neutrino Earth core radiography

1. Introduction

Neutrino absorption radiography (C. Kuo et al.(1995), P. Jain et al.(1999), M. M. Reynoso textitet al. (2004)) has been considered as a promising method to probe the density profile of the Earth. It is expected to be a good complement to the seismic tomography because it handles the density structure in the Earth’s mantle and core directly. When neutrino radiographs are combined with geo-dynamic simulations and seismic data, the radiographic images allow us to address many regional and global tomographic studies of the mantle and core.

The principle of the neutrino radiography is simple. Due to their low interaction cross section, neutrinos can penetrate full-length of the Earth’s diameter. For ‘soft’ neutrinos with energy up to sub-TeV the Earth is almost transparent, while TeV energy neutrinos have larger cross section to Earth’s matter thus the probability of absorption rises as energy increases. By observing the deficit of high-energy neutrino due to the absorption, a radiograph of neutrino is obtained as we get X-ray radiograph with X-ray, however, many practical difficulty have been preventing us from utilizing neutrino as a probe of the Earth.

First, it is challenging to detect neutrinos because of their low cross section. In order to obtain clear radiograph one need to require sufficient statistics of high energy neutrinos. The size of detector must be large enough to gain statistics within the life time of the experiment.

Second, preparing high energy neutrinos over a few TeV energy is not straightforward. One possibility is using neutrinos from cosmic sources such as active galactic nuclei (AGN) or gamma ray bursts (GRB), however, none of neutrino telescope observed the signal from these cosmic sources yet. Another candidate is atmospheric neutrinos produced in collisions of high energy cosmic rays with nuclei in the Earth’s atmosphere. They are already detected, but most of them are below TeV energy because their energy spectrum falls down steeply with $\sim E_{\nu}^{-3.7}$. For this nature a large detector is required again.

Recent development of technique to construct large scale neutrino telescopes such as AMANDA (J. Ahrens et al.(2004)) and KM3NeT (M. Bouwhuis et al.(2007)) broke through these difficulties. Although their detection volume is not sufficient yet, their successor IceCube (A. Achterberg et al.(2006), J. Ahrens et al.(2004)) and KM3NeT will have a cubic kilo meter detection volume. A recent study by M. C. Gonzalez-Garcia et al.(2008) presents a calculation of five sigma separation between Earth’s mantle and core with IceCube detector, using atmospheric neutrinos with statistics of $\sim$850K events after 10 years operation.

In this paper we use AMANDA-II 3.8 years of neutrino data accumulated from 2000 to 2006 (R. Abbasi et al.(2008), http://www.icecube.wisc.edu/science/data/amanda7year/) instead. The purpose of this study is to examine the idea of neutrino radiography using atmospheric neutrinos and clarify problems for applying this analysis to IceCube data. The results are discussed in Section 4 and the outlooks for the future analysis with IceCube is described in Section 5.

2. AMANDA-II detector and detection principle

The AMANDA-II detector is an optical Cherenkov neutrino detector deployed into deep glacier ice at the South Pole. A total of 677 optical modules (OM) are attached to 19 strings and deployed between 1500 m to 1950 m depth within a 200 m diameter in glacial ice at the South Pole. Each OM contains a 20 cm photomultiplier tube (PMT) encapsulated by a glass pressure sphere.

When a muon neutrino path through the AMANDA-II detection volume, occasionally it interact with a nuclear in ice or bed rock and generates a muon. The angle between neutrino and produced muon in this energy range is less than 1° then it is reasonable to use muon direction as a representative of original neutrino direction within systematics of detector. Cherenkov radiation is emitted by this muon inside AMANDA-II volume and propagate through dark clear glacier ice. Once an OM capture the Cherenkov right, the output pulse from PMT is transfered to ice surface then
recorded after trigger process.

From the recorded data, we obtain a leading edge time of PMT pulses from each triggered OM. Muon tracks are reconstructed within a median space angle resolution of 2.5° using the leading edge times and optical properties of South Pole ice (M. Ackermann et al. (2006)). For energy estimation, number of fired OMs (n-channel, Nch) is used as a simple indicator of muon energy at AMANDA-II depth.

3. Data and analysis method

The key strategies of neutrino absorption radiography are simply summarized as follows.

1) Compare event rate as a function of reconstructed zenith angle (θ) between

2) Event samples extracted with various energy threshold

Our ultimate goal is to observe a significant deficiency of event rate in vertically upward going direction. In order to accomplish the goal, these procedures are translated into two requirements:

1) Square root of number of event per zenith bin need to be less than the deficiency

2) Find an energy parameter and conversion function to obtain energy of neutrino at Earth’s surface

In this section we present how these requirements are considered.

The total 3.8 years of data analyzed in this paper were recorded by AMANDA-II neutrino telescope during a period from 2000 to 2006 (R. Abbasi et al. (2008), http://www.icecube.wisc.edu/science/data/amanda7year/). After background rejection and event purification, 6595 events are survived with 1.5° ~ 2.5° median accuracy of reconstruction angle, depending on its energy and zenith angle. They are all upward going events in AMANDA-II coordinate (zenith angle over 90 degree) which are regarded as "neutrino-origin" muon events. Since a set of downward going events (zenith angle less than 90 degree) contains Ω(6) higher number of atmospheric muons compared with the neutrino-origin muons at trigger level, all downward going events are removed from this data.

The data also include a simple energy estimator, number of triggered OMs (Nch). Fig.2 shows distributions of Nch in different track directions. As a result of a soft energy spectrum of atmospheric neutrino¹, the number of events falls steeply as Nch increases.

This Nch parameter roughly indicates an energy of muon at the AMANDA-II detector, however, it highly depends on the muon track angle and the minimum distance from AMANDA-II center to the muon track. To translate the Nch parameter into a geometry-independent energy estimator, we used muon energy curves as a function of Nch threshold obtained from a set of Monte-Carlo simulation (Fig.3). This curve gives an average muon energy for events which Nchs are greater than an Nch threshold value.

According to the recent study of Earth’s core radiography (M. C. Gonzalez-Garcia et al. (2008)), the deficiency of event rate due to the Earth’s core will be ~ 20 % at muon energy over 10 TeV on the assumption of Preliminary Reference Earth Model (PREM). This energy threshold is far from the possible highest energy threshold for AMANDA-II 3.8 years data with reasonable event statistics, though (see Fig.2 for Nch over 200). Instead, we used lower Nch threshold up to 50 with large zenith(θ) bins: 90° < θ < 120° (0 > cos θ > −0.5) and 120° < θ < 180° (−0.5 > cos θ > −1).

There is no search for diffuse extraterrestrial neutrino source with this 3.8 years AMANDA-II data yet. However, considering current diffuse flux limit $E^2 \Phi < 7.4 \times 10^{-11}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (A. Achterberg et al. (2007)), we regard theses events are predominantly from atmospheric neutrinos at least for Nch range up to middle-high, e.g., Nch > 100.
With this constraint each zenith bin contains at least 500 events.

One drawback having large zenith bins is considerable differences of detection efficiency between neighboring $\cos \theta$ bins. The difference of event rate in neighboring $\cos \theta$ bins is thus regarded as a convoluted effect of zenith dependence of detection efficiency, atmospheric neutrino flux, and neutrino absorption. In order to eliminate zenith asymmetry as much as possible, we took a reduction rate of number of events within a $\cos \theta$ bin as a function of lowest Nch threshold, then took a ratio of reduction rates between different $\cos \theta$ bins. After the procedure, the ratio curve dominantly contains asymmetry of atmospheric neutrino flux with a tiny deficit due to the neutrino absorption.

Two translations are applied to the Nch threshold parameter. A translation from Nch to muon energy at AMANDA-II depth is carried out using Fig.3 followed by an another conversion from muon energy to primary neutrino energy at the Earth’s surface with Fig.4.

As an origin of reduction curve, we took primary neutrino energy $\log_{10} E_{[\text{GeV}]} = 2.97$. It corresponds Nch threshold $n_0 = 43$ for $\cos \theta < -0.5$ and $n_0 = 25$ for $\cos \theta > -0.5$. The reduction rate $r(\theta, n)$ is then calculated with Eq.1:

$$ r(\cos \theta, n) = \frac{\text{Number of events in } \theta (\text{Nch} > n)}{\text{Number of events in } \theta (\text{Nch} > n_0)} $$

(1)

The ratio of declination between different zenith angles are obtained as follows.

$$ \text{ratio}_{E_{\nu}} = \frac{r(\cos \theta < -0.5, E_{\nu})}{r(\cos \theta > -0.5, E_{\nu})} $$

(2)

4. Results and discussions

The reduction curves and ratio curve obtained from AMANDA-II 3.8 years data are shown in Fig.5 and Fig.6 respectively. Error bars in y-axis are estimated from event statistics and no systematics error is took into account. The x-axis errors are from wide distribution in Nch vs LogE plane (see Fig.3). Numerical table of reduction curve is shown in Table.1.

Ratios from two numerical simulations are superimposed into Fig.6. The blue square points show the simulation using PREM model for the Earth’s density. The other simulation, green triangle points, represents an extreme case: the density of the Earth is 0 g/cm$^3$ (No Earth).

Comparing these simulations with data, we set following discussion items.

1) The simulation and data matches within the error bars except for the highest energy point.

2) The absorption effect due to the Earth’s matter is by a factor of five or more smaller than current statistical
errors at $\sim$TeV neutrino energy.

3) The error bars in x-axis (energy) give uncertainty to the inclination of ratio curve by a factor of two or more.

First of all, it is encouraging that the data and simulation shows consistent behavior. Considering 2) and 3) it is hard to derive any numerical information for the Earth’s density, however, this is still prospective result towards the next study performed with the IceCube data.

From the second item we estimate the required statistics to observe a deficit due to the Earth’s matter in the energy range of neutrino $2.97 < \log_{10}E_{\nu}/[\text{GeV}] < 3.12$. The difference of ratio curves between ‘PREM’ model and ‘No Earth’ model is 0.015 at the highest energy point while the error bars of data in y-axis is $\sim 0.075$. For three sigma separation, we need to reduce the error bars less than $\sim 0.005$ by increasing statistics $\sim 225$ times or more. Since the current statistics at highest energy bin is $\sim 500$, the required statistics per bin is 112500. Comparing the estimated number of event with ten years operation of IceCube in M. C. Gonzalez-Garcia et al. (2008), this number corresponds roughly ten years for IceCube. This livetime is feasible, though, more efficient method is desired for our ultimate goal described in Section 3.

Considering the third item, we learned limits of Nch parameter. Although the Nch has been regarded as a robust energy estimator, the energy resolution and sensitivity for high energy muon are not sufficient for our purpose. As Fig.3 shows, an average energy of muon can be determined from an Nch threshold within a few percent at least within the energy range we used for this study. However, the width of distribution of muon energy for an Nch threshold is much wider than a few percent as Fig.7 shows. Applying high Nch cut result in a significant reduction of surviving number of events, for example, we lose 230 events of TeV muons while 150 events of TeV muons remain in survived events if Nch $> 50$ cut is applied, in the case of zenith angle $-0.5 > \cos \theta > -1$. This rejected 230 events are only $\sim 6\%$ of total number of rejected events, though, still the loss makes our analysis difficult at higher energy range. To improve the energy resolution, we need to use the IceCube detector as described in the next section.

5. Outlook for IceCube detector

In 2007, AMANDA-II is officially merged into IceCube detector. The AMANDA-II is now surrounded by the IceCube strings deployed in depths between 1450 m to 2450 m with 60 digital optical modules (DOM) attached. By the end of February 2008, 40 strings out of 80 strings are successfully deployed then physics run started in the end of May. The accumulated neutrino events with IceCube 22 strings during 271 days livetime (2007-2008) reached to $\sim$4000 events. Since the detection volume of IceCube 40 strings is almost double from IceCube 22 strings, data in 2008-2009 is expected to exceed AMANDA-II 3.8 years statistics.

One of a remarkable improvement from AMANDA-II to IceCube is the digital recording of waveforms. The waveform from PMT is immediately converted into digital waveform inside the optical module, then transferred to the ice surface. This in situ digitization solved a problem in AMANDA era: analog waveforms from PMTs are stretched out during the propagation over 1 km distance to the ice surface. From the digital waveform we obtain number of photons with their arriving time. Using the two-dimensional information of arrival photons, we are developing geometry-independent energy reconstructions to get better energy resolution.

New Monte-Carlo study including detailed detector simulation is under preparation to understand systematics errors due to detector configuration and glacier ice property. As a candidate of another systematics, a study of seasonal vari-
ation of density of atmosphere is ongoing: the atmospheric neutrino flux is expected to change as density of atmosphere changes. As soon as these preparations are done, we repeat this analysis and improve our analysis method with better understanding of systematics errors.

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References
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Table 1. Numerical value of ratio of reduction curve. The field Nch shows the Nch threshold which actually used to extract higher energy samples.