TESTING ALTERNATIVE OSCILLATION SCENARIOS WITH ATMOSPHERIC NEUTRINOS USING AMANDA-II DATA FROM 2000 TO 2003

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The AMANDA-II neutrino telescope detects upward-going atmospheric muon neutrinos penetrating the Earth from the Northern Hemisphere via the Cherenkov light of neutrino-induced muons, allowing the reconstruction of the original neutrino direction. Due to the high energy threshold of about 50 GeV, the declination spectrum is minimally affected by mass-induced neutrino oscillations; however, alternative oscillation models predicting effects at high energy can be tested and constrained. Of particular interest are models that allow one to test Lorentz invariance and the equivalence principle. Using the AMANDA-II data from the years 2000 to 2003, a sample of 3401 candidate neutrino-induced events was selected. No indication for alternative oscillation effects was found. For maximal mixing angles, an upper limit is set on both the Lorentz violation parameter $\delta c/c$ and the equivalence principle violation parameter $2|\phi|\delta\gamma$ of 5.3×10^{-27} at the 90% confidence level.

1. Introduction and detector description

Cosmic ray particles entering the Earth's atmosphere generate a steady flux of secondary particles, including muons and neutrinos. High energy muons pass through the atmosphere and can penetrate several kilometers of ice and rock, while atmospheric neutrinos of energies only above roughly 40 TeV start to be absorbed in the Earth. Lower energy muon neutrinos penetrating the diameter of the Earth can oscillate into tau neutrinos. However, the oscillation maxima at 30 GeV[1] and below are beneath the AMANDA-II threshold. Departures from conventional mass-induced oscillations could emerge at higher neutrino energies due to relativity-violating effects (see below). Such mechanisms would distort the expected angular distribution and energy spectrum of atmospheric neutrinos and could be detectable by AMANDA-II.

The AMANDA-II neutrino telescope is embedded $1500 - 2000$ m deep in the transparent and inert ice of the Antarctic ice sheet, close to the geographic South Pole. AMANDA-II consists of 677 optical modules (OMs) on 19 vertical strings, which are arranged in three approximately concentric circles of 60 m, 120 m and 200 m diameter. Muons produced in ν_μ-nucleon interactions can be directionally reconstructed by observing the Cherenkov radiation that propagates through the ice to the array of photosensors. To ensure that the observed muon is due to a neutrino interaction, the Earth is used as a filter against atmospheric muons, and only tracks from the Northern Hemisphere (declination $\delta > 0^\circ$) are selected.

2. Phenomenology of standard and alternative neutrino oscillations

It is commonly accepted that standard (mass-induced) $\nu_\mu \rightarrow \nu_\tau$ oscillations[a] are responsible for the measured deficit of atmospheric muon neutrinos[1]. Atmospheric neutrino data can also be used to test non-standard oscillation mechanisms that lead to observable differences at higher neutrino energies. Various new physics scenarios can result in neutrino flavor mixing. Two of these scenarios, which can be described in a mathematically analogous way, have been tested in this analysis. The underlying theories assume small deviations from the principles of the theory of relativity and lead to measurable neutrino oscillations:

- In theories predicting violation of Lorentz invariance (VLI), a set of additional neutrino eigenstates with different maximal attainable velocities (MAV) c_n/c is introduced, violating special relativity[2].

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[a] In the regime of atmospheric neutrino oscillations, it suffices to consider a two-flavor system of eigenstates (ν_μ, ν_τ).

- In theories predicting violation of the weak equivalence principle (VEP), gravitational neutrino eigenstates are introduced which couple with distinct strengths γ_n to a gravitational potential ϕ, conflicting with the universal coupling assumed in general relativity[3,4].

The main difference between these oscillation scenarios and standard oscillations is the linear energy dependence of the oscillation frequency, shifting observable oscillation effects into the energy range of AMANDA-II. For the sake of simplicity, we will focus on the VLI scenario. As both theories are mathematically equivalent, the results can be transferred to the VEP case by simply exchanging the relativity-violating oscillation parameters $\delta c/c \to 2|\phi|\delta\gamma$ and mixing angles $\Theta_c \to \Theta_\gamma$.

Combining standard and VLI oscillations, one obtains three systems of neutrino eigenstates (flavor, mass, and MAV eigenstates), resulting in a total of 5 oscillation parameters: the mass-squared difference Δm^2, two mixing angles Θ_m and Θ_c, the VLI parameter $\delta c/c$, and a complex phase η. Fixing $\Delta m^2 = 2.3 \times 10^{-3}\,\mathrm{eV}^2$ and $\Theta_m = 45°$, the survival probability may then be written as:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\Theta\ \sin^2(\Omega\ L) \tag{1}$$

$$2\Theta = \arctan(s/t) \qquad\qquad \Omega = \sqrt{s^2+t^2} \tag{2}$$

$$\begin{aligned} s &= 2.92 \times 10^{-3}\,|\,1/E_\nu + 8.70 \times 10^{20}\ \delta c/c\ \sin 2\mathit{\Theta}_c\ E_\nu\ \mathrm{e}^{i\eta}|\ , \\ t &= 2.54 \times 10^{18}\ \delta c/c\ \cos 2\mathit{\Theta}_c\ E_\nu\ . \end{aligned} \tag{3}$$

Here the the muon neutrino path length L is expressed in km and the neutrino energy E_ν in GeV. For the given set of parameters, one can observe a significant effect within the analyzed energy range $(100\,\mathrm{GeV} - 10\,\mathrm{TeV})$ and declination range ($\delta \geq 20°$), for certain values of Θ_c and $\delta c/c$.

The VLI effects can also be viewed in terms of the Standard Model Extension, an effective quantum field theory which adds all coordinate-independent renormalizable Lorentz-violating operators to the Standard Model[5,6]. In particular, the above oscillations correspond to non-zero and differing eigenvalues of c_L, the dimensionless coefficient of the Lorentz-violating Lagrangian term $\frac{1}{2} i (c_L)_{\mu\nu ab} \bar{L}_a \gamma^\mu \overleftrightarrow{D}^\nu L_b$ [7]. Additionally, in this scenario only rotationally invariant (time) components of c_L are non-zero (so-called "fried chicken" models), and we consider only a two-flavor system. With these restrictions, $\delta c/c$ in eq. 3 is equivalent to the difference in eigenvalues $(c_a - c_b)$ of the 2×2 matrix c_L^{TT}.

3. Data selection and analysis method

The data analyzed in this analysis are selected from 7.9×10^9 events recorded from 2000 to 2003, representing a total livetime of 807.2 days. Quality selection criteria based on various track reconstruction quantities are used to reduce contamination of the sample by mis-reconstructed atmospheric muons to a level of approximately 4% (see ref. 8 for more details). The resulting number of selected neutrino candidate events is 3401. Reconstructed declination and the number of OMs triggered in an event (N_{ch}, an energy estimator) are used as observables to search for any deviations in the atmospheric neutrino spectrum that are dependent on flight length or neutrino energy. A full simulation chain, including neutrino absorption in the Earth, neutral current regeneration, muon propagation, and detector response is used to simulate the response of AMANDA-II to atmospheric neutrinos[9,10]. The expected atmospheric muon neutrino flux before oscillations is taken from Lipari[11].

The analysis method uses a χ^2-test to compare the declination and N_{ch} distributions of data with Monte Carlo simulations including VLI oscillation effects. The systematic uncertainties affecting the Monte Carlo prediction are integrated into the χ^2 expression: uncertainties in the normalization due to detector response and theoretical models of atmospheric neutrino flux (30%); uncertainty due to the relative production rate between kaons and pions (6%); and uncertainty in the sensitivity of the OMs (11.5%). The optimal binning of the χ^2 expression is determined using toy Monte Carlo studies, and the exclusion regions for alternative oscillation effects are obtained by scanning through the oscillation parameter space.

4. Results and Outlook

The analysis of the final atmospheric neutrino sample finds no evidence for alternative oscillations, and a preliminary upper limit on the VLI parameter $\delta c/c$ is set of 5.3×10^{-27} at the 90% confidence level, for nearly maximal mixing angles $\Theta_c \approx \pm\pi/4$. The dependence on the unconstrained phase η is found to be small (see figure 1); the most conservative limit is obtained for $\cos\eta = 0$. The limit can also be interpreted in the context of VEP theories, leading to an upper limit of $2|\phi|\delta\gamma \leq 5.3 \times 10^{-27}$. This result is competitive with the limits obtained using data from Super-Kamiokande[12] and MACRO[13]. However, AMANDA is not sensitive to small mixing angles due to the systematic errors and its higher energy threshold.

A likelihood analysis of the 2000-2006 AMANDA-II data sample is

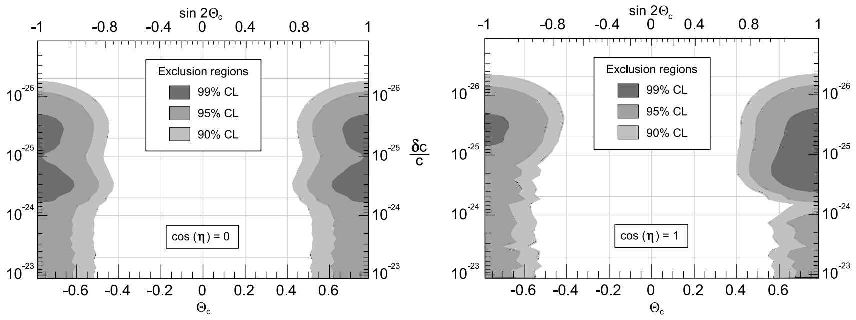

Figure 1. Shown are preliminary exclusion regions for VLI (VEP) oscillation effects, left for $\cos\eta = 0$, right for $\cos\eta = 1$.

in progress, with improved systematic error estimation and increased sensitivity[14]. This analysis will also extend the technique to search for evidence of quantum decoherence resulting from interaction of neutrinos with the background space-time foam[15]. The next-generation IceCube detector, when completed in 2010, will be able to extend the sensitivity to VLI effects by about one order of magnitude[16].

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