Atmospheric Neutrinos and Boosted Dark Matter at Super-Kamiokande

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The mixing or neutrino flavor states has now been established for some time. This mixing was first observed as the "solar neutrino problem" in the 1960's, when Ray Davis and John Bahcall measured the flux of solar neutrinos, and found it to be smaller than predicted. Around the turn of the 21st century, measurements of atmospheric neutrinos as Super-Kamiokande (SK) and solar neutrinos at SK and the Sudbury Neutrino Observatory (SNO) finally confirmed that neutrino mixing was the cause of the solar neutrino problem.

The theory of neutrino mixing relies on weak interaction neutrino eigenstates being different from neutrino mass eigenstates. The flavor eigenstates ν_α are related to the mass eigenstates ν_i by

$$|\nu_\alpha\rangle = \sum_i^3 U^*_{\alpha,i}|\nu_i\rangle, \tag{1}$$

where U is the 3x3 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

Here $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$. Propagation of these states according to their vacuum Hamiltonians leads to the standard oscillation formula for relativistic neutrinos in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Delta_{ij} \pm 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Delta_{ij} \tag{3}$$

where

$$\Delta_{ij} = \frac{1.27\Delta m_{ij}^2(\text{eV}^2)L(\text{km}^2)}{E(\text{GeV})}\ ,\ \Delta m_{ij}^2 = m_i^2 - m_j^2 \tag{4}$$

and the sign before the second summation in Eq. (3) is positive for neutrinos and negative for anti-neutrinos. Neutrino oscillations in vacuum are thus fully described by 6 parameters: the 3 mixing angles $\theta_{13}, \theta_{12}, \theta_{23}$, the two mass splittings $\Delta m_{21}^2, \Delta m_{31}^2$, and the CP violating phase δ_{cp}. Of these parameters, $\theta_{13}, \theta_{12}, \Delta m_{21}^2$, and $|\Delta m_{31}^2|$ have been measured to high precision. The parameter θ_{23} has also been measured, but a larger uncertainty remains in its value than in the other two mixing angles. The parameter δ_{cp} and the sign of Δm_{31}^2 remain essentially unknown. The sign of Δm_{31}^2 is often referred to as the mass hierarchy (or mass ordering), because it's sign indicates whether the hierarchy is of the form $m_1 < m_2 < m_3$ (normal), or $m_3 < m_1 < m_2$ (inverted).

At Super-Kamiokande, we can probe these three unkowns of neutrino oscillation using atmospheric neutrino measurements. Low energy ("Sub-GeV") "e-like" samples are sensitive to the value of δ_{cp}, as values closer to $\pi/2$ predict less $\nu_\mu \to \nu_e$ oscillation, while values closer to $3\pi/2$ predict more $\nu_\mu \to \nu_e$ oscillation. Higher energy ("Multi-GeV") "μ-like" samples are sensitive to the value of $\sin^2\theta_{23}$, as values closer to 0.4 predict more ν_μ survival, while values closer to 0.6 predict less ν_μ survival. Finally, Multi-GeV e-like samples are sensitive to the mass hierarchy through matter effects. When neutrinos travel through matter, the effective Hamiltonian is modified from its vacuum form due to coherent ν_e-electron scattering (presented here in mass eigenstate basis):

$$H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U \tag{5}$$

where $a = \pm\sqrt{2}G_F N_e$, G_F is the Fermi constant, N_e is the electron density, U is the PMNS matrix, the plus sign is for neutrinos, and the minus sign for antineutrinos. This results in a resonant enhancement in the $\nu_\mu \to \nu_e$ oscillation for neutrinos with energies around 5 to 10 GeV crossing the mantle of the Earth. Importantly, the enhancement occurs for *either* neutrinos or antineutrinos, depending on the hierarchy. Although SK is not directly sensitive to lepton charge, samples can be created which are more or less populated with neutrinos or antineutrinos. By looking at which samples this resonance is observed in, we can attempt to extract a hierarchy preference from SK data. In my thesis, I will present an analysis which looks for signs of matter effects in SK atmospheric neutrino data. Since sensitivity to mass hierarchy at SK (or future atmospheric neutrino experiments) is dependent on matter effects, observation of these effects is an important step towards mass hierarchy determination.

Recently, a 2σ tension has appeared between the measurements of θ_{23} by T2K and NOνA. While 2σ tensions are often the result of simple statistical fluctuations, this could potentially be the first sign of some new physics. Particularly, there have been recent suggestions that this tension can be alleviated by introducing a decoherence term to the standard oscillation parameters. Such decoherence terms are essentially phenomenological at present, often motivated by quantum gravity. They come from introducing an additional dissipative term to the Louiville equation:

$$\frac{d\rho}{dt} = -i[H, \rho] - \mathcal{D}[\rho] \tag{6}$$

where ρ is the density matrix, H is the system Hamiltonian, and $\mathcal{D}[\rho]$ is the additional dissipative term. This leads to oscillation terms that go as $e^{-\Gamma L} \cos \frac{\Delta m^2 L}{2E}$, instead of the usual $\cos \frac{\Delta m^2 L}{2E}$. These explanations rely on a decoherence parameter strength which is allowed by previous SK limits. However, those limits were set with only about a quarter of the SK data that has now been accumulated. Those limits were also based on a 2-flavor neutrino model, and did not include matter effects. I will calculate new limits on decoherence using SK atmospheric neutrinos, using the 3-flavor neutrino model and matter effects, to find whether the decoherence explanation of the T2K-NOνA tension remains viable.

SK can also be used for astrophysical searches, and there are currently multiple SK dark matter searches. While there has long been ample evidence for the existence of dark matter, the specific properties and identity of dark matter remain elusive. The ΛCDM cosmology, which consists of long lived dark matter which is non-relativistic ("cold") at current times and a cosmological constant Λ which corresponds to dark energy, has been well supported by cosmological observations. Under this cosmology, the dark matter abundance has been measured by Planck and WMAP through observation of the Cosmic Microwave Background (CMB) to account for about 25% of the energy density of the Universe. However, beyond it's existence and abundance, little else is known about the properties of dark matter. A promising possible cold dark matter particle is the Weakly Interacting Massive Particle (WIMP), but thus far attempts at it's direct detection have left such a particle undiscovered. Indirect detection searches for dark matter through the detection of it's Standard Model annihilation products, as well as searches for dark matter produced at particle accelerators have thus far similarly produced null results.

With the properties of dark matter so uncertain, various possibilities must be considered. One possibility is that some dark matter is in fact not cold, but is highly relativistic and has been produced at late times thus earning the name "boosted" dark matter. Boosted dark matter could exist as a subdominant dark matter component, with a dominant cold dark matter component accounting for most of the dark matter energy density of the Universe. In this way, boosted dark matter can remain consistent with ΛCDM. The subdominant boosted dark matter can be the same particle as the dominant cold dark matter, or it can be a different, lighter particle. Boosted dark matter can be produced from the dominant cold dark matter through a variety of processes, including annihilation, semi-annihilation, 3$\rightarrow$2 self-annihilation, and decay. Boosted dark matter can then be observed scattering off electrons or nuclei in large volume terrestrial detectors. Current direct detection limits can be evaded in multi-component models by having only the boosted dark matter species couple directly to Standard Model particles or in single-component models by invoking a spin dependent dark matter-nucleon cross section. We can search for boosted dark matter in SK by looking for elastically scattered electrons with energies greater ranging from 100 MeV to 1 TeV. This is a class of events that has never before been studied at SK; while elastically scattered electrons have been studied extensively in the solar neutrino energy range (1-20 MeV), the neutrino-nucleus cross section dominates the neutrino-electron cross section for neutrinos above 100 MeV. Since boosted dark matter is likely to originate in regions of high dark matter density, we look for elastically scattered electrons which point back to the Galactic Center or the Sun. We select events which could be elastically scattered electrons with a simple cuts-based approach, using standard SK reconstruction variables. We count the number of events in cones of different sizes around the Galactic Center and Sun, and compare these counts to the expected background from atmospheric neutrinos. The background is estimated by counting events in sidebands, which gives us a completely data-driven, MC free background estimate. The analysis is purposefully kept simple and model independent so that our results can be easily adapted to any model that predicts a source of particles from the Galactic Center or Sun which would scatter electrons to energies greater than 100 MeV. In my thesis, I will present the results of this search, and demonstrate the power of the result to constrain boosted dark matter theories.

Thesis Outline

1. **Introduction**
    - **This Thesis**
        - **What has come before at SK**
        - **What is to come in thesis.**
    - **History of Neutrinos**
        - **A brief history of neutrino physics. Proposal by Pauli, discovery, solar neutrino problem, discovery of oscillation.**
    - **History of Dark Matter**
        - **A brief history of dark matter physics. Galactic rotation curves, bullet cluster, null results so far**
2. **Super-Kamiokande Detector**
    - **Overview**
    - **The Tank**
    - **Cherenkov Radiation**

- **Photomultiplier Tubes**
- **Electronics and Data Acquisition**
- **Water System**
- **Detector Calibration**

3. **Data Processing**
   - **Data Reduction**
     - **Fully Contained Events**
     - **Partially Contained Events**
     - **Upward Going Muons**
   - **Event Reconstruction**
     - **Vertex Reconstruction**
     - **Ring Counting**
     - **Particle ID**
     - **Energy Reconstruction**
     - **decay electrons**
     - **neutron tagging**

4. **Atmospheric Neutrino Analysis**
   - **Neutrino Oscillations**
     - **In Vacuum**
     - **In Matter**
     - **Current state of parameters**
       - **recent results**
   - **Atmospheric Neutrino Production**
   - **Atmospheric Neutrino Oscillations**
     - **which parameters effect**
     - **oscillograms**
   - **Atmospheric Neutrino Simulation**
   - **Matter Effects Analysis**
     - **Analysis Technique**
       - **Subsamples**
       - **Binning**
       - **systematic errors**
       - **sensitivity**

        * results
- Decoherence Analysis
    - Motivation
        * T2K-NOνA tension
    - theory
        * Lindblad Equation
        * 2-flavor
        * 3-flavor (vac)
        * 3-flavor (matter)
    - sensitivity
    - results

5. Boosted Dark Matter

- Evidence for dark matter
    - Galactic rotation curves, bullet cluster
    - CMB measurement of Universe composition
- Possible Dark Matter theories
    - neutrinos
        * idea, limits (mass too small)
    - axions
        * idea, limits (experimental)
    - WIMPs
        * idea
        * limits (direct detection, indirect detection, accelerators)
- Boosted Dark Matter Theory
- Galactic Halo Models
- Event Selection
- Signal MC
- Ring Counting
- Analysis Technique
- Background Estimation
- results

6. Conclusion