Prospects for a Search for Sterile Neutrinos Using the Sudbury Neutrino Observatory

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Outline

Goal: To determine whether or not it is possible to use SNO to search for sterile neutrinos

- Sudbury Neutrino Observatory
- Neutrino Oscillations
- Sterile Neutrinos
- Detector Yield Calculations
- Day-Night Asymmetry
- Results
- Conclusions

“CAUTION: Every year several REU students are killed.”
• Heavy Water Čerenkov Detector
• 2 km underground, INCO Ltd. Creighton mine
• 12 m diameter AV, filled with heavy water
• Light water extending from the AV to the edges of the SNO cavity
• 18 m diameter PMT support structure

“No. Did you?”
Detection of Neutrinos

\[ \nu_e + d \rightarrow p + p + e^- \]  \hspace{1cm} (CC)

\[ \nu_x + d \rightarrow p + n + \nu_x \]  \hspace{1cm} (NC)

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]  \hspace{1cm} (ES)

Three Phases – Heavy Water, Salt, NCD

“CORE DUMPED!”
Neutrino Oscillations

Equations? AHHHHH!

• Three flavors of neutrinos, called the “weak states” - $\nu_e$, $\nu_\mu$, $\nu_\tau$

• Massless in the Standard Model

• “Mass states” $\nu_1$, $\nu_2$, $\nu_3$. Weak states are a linear combination of Mass States:

$$|\nu_x\rangle = \sum_m U_{xm} |\nu_m\rangle$$

• $U$ is the neutrino mixing matrix, similar to the CKM matrix for quark mixing

• Assume only two neutrino generations:

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

“MSG’d!”
Neutrino Oscillations, Cont.

Otherwise known as “Oh god, not more equations!”

• Time evolution of a state is determined by its energy:

\[ |\nu_e(t)\rangle = \cos \theta \exp[-i(E_1/\hbar)t]|\nu_1\rangle + \sin \theta \exp[-i(E_2/\hbar)t]|\nu_2\rangle \]

• Energy of a state is related to its mass:

\[ E_k = \sqrt{p^2c^2 + m_k^2c^4} \]

• Starting from the fact that the probability an electron neutrino will oscillate into a muon neutrino is given by the absolute square of the amplitude of \( \langle \nu_\mu | \nu_e(t) \rangle \):

\[ P(\nu_e \rightarrow \nu_\mu) = 1 - \sin^22\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right) \]

\[ P(\nu_e \rightarrow \nu_e) = 1 - P(\nu_e \rightarrow \nu_\mu) \]

Neutrino oscillation can be understood in a very simple way. What happens is that the lighter mass states in the original \( \nu_x \) travel faster than the heavier ones, and get ahead of the latter. Thus, the various \( \nu_m \) components of the beam get out of phase with one another, and do not add up to a \( \nu_x \) anymore. Thus, as it travels, the beam picks up components corresponding other flavors.

- B. Kayser, “The Physics of Massive Neutrinos”

“Accessing Random Insult Generator… ‘You suck at life.’ “
Sterile Neutrinos

Why am I wasting your time talking about them?

• Three neutrinos -> Three Mass Scales
• Three different types of experiments measure the three different mass scales
• Experimentally established limits:
  \[ \Delta m^2_{12} < 10^{-5} \]
  \[ \Delta m^2_{23} < 10^{-3} \]
  \[ \Delta m^2_{13} > 10^{-1} \]
• \[ \Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13} \] Doesn’t add up!
• Need at least one more neutrino
• LEP says there are only three active neutrinos
• Any additional neutrinos must not interact with the Z, must be sterile

“Wheeeeeeeeeeeeee!”
Detector Yield

In other words, just how many of these neutrinos will we see?

\[ Y = U\epsilon_n \int dt \int_0^V dV \int_{T_{th}}^\infty R_{NC}(T) dT \int_0^1 W(\cos \theta_z) \Phi_{SSM}(E_\nu) \sigma_{\nu_d}^{NC}(E_\nu) P(\nu_\alpha \rightarrow \nu_\beta) \cos \theta_z dE_\nu \]
Detector Yield

Still Explaining the Big Equation

\[ Y = U \epsilon_n \int_{0}^{V} \int_{0}^{T_{th}} R_{NC} (T) dT \int_{0}^{\infty} \int_{-1}^{1} W (\cos \theta_z) \Phi_{SSM} (E_{\nu}) \sigma_{\nu d}^{NC} (E_{\nu}) P (\nu_a \rightarrow \nu_s) d\cos \theta_z dE_{\nu} \]

“Who is your Daddy, and what does he do?”
Day – Night Asymmetry

How we actually “see” the sterile neutrinos in SNO

\[ N = U \epsilon_n \int dt \int_0^V dV \int_{T_{th}}^\infty R_{NC}(T) dT \int_0^\infty \int_{-1}^0 W(\cos \theta_z) \Phi_{SSM}(E_\nu) \sigma_{\nu \nu d}^{NC}(E_\nu) P(\nu_a \rightarrow \nu_s) d\cos \theta_z dE_\nu \]

\[ D = U \epsilon_n \int dt \int_0^V dV \int_{T_{th}}^\infty R_{NC}(T) dT \int_0^\infty \int_0^1 W(\cos \theta_z) \Phi_{SSM}(E_\nu) \sigma_{\nu \nu d}^{NC}(E_\nu) P(\nu_a \rightarrow \nu_s) d\cos \theta_z dE_\nu \]

\[ A = 2 \frac{N - D}{N + D} \]

• Different values of the length of travel of the neutrino during night and day change the probability of oscillating into a sterile state

• Non-zero asymmetries should be observed if sterile neutrinos exist

• Can SNO see them?

“Jobs and Growth!”
Results

Look at the pretty graphs that I made!

“\text{I’m a cop, you idiot!}”
Conclusions

Last Slide. Hooray!

• Limits on the parameters for detecting steriles in SNO.

• Currently, these limits would be:

  \[ 10^{-2} < \sin^2 2\theta \]
  \[ 10^{-5} < \Delta m^2 < 10^{-2} \]

• Can sterile neutrinos be detected at all through a day – night asymmetry?
  Yes, but whether or not a non-zero asymmetry can be measured to 3\( \sigma \) is not yet known.

• Much more work is required

  Non-constant Earth-Sun Distance

  Matter effects

  Extension of \( \sigma_A \) to the entire data set is only an approximation. N and D should be higher in second and third phases.

  Generalize model to include mixing between sterile and all three active neutrinos.

  Additional sterile neutrinos?

“Stop Whining!”
Acknowledgements
I lied, but this really is the last slide

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“I think the tide’s coming in.”