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

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REU Presentations Presents “Memories of the Summer”, appearing on the bottom of this presentation.

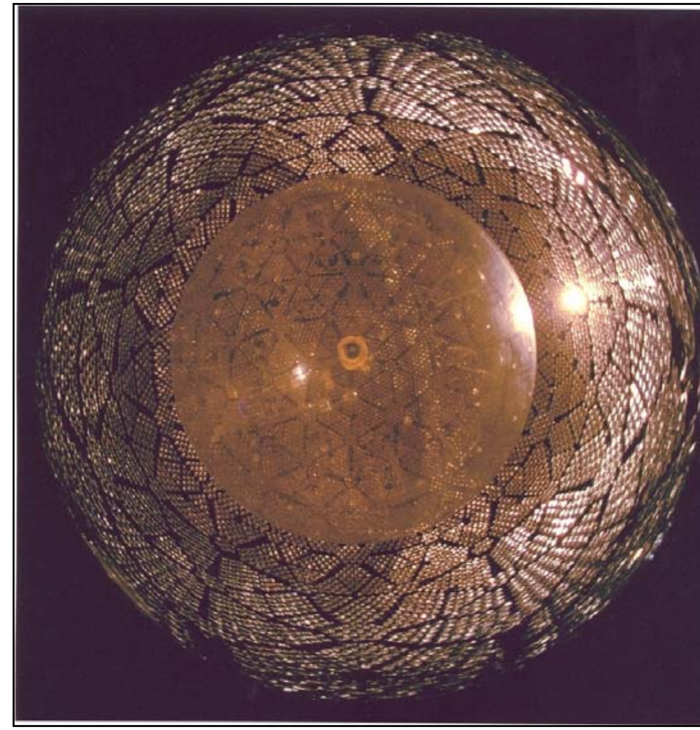
Outline

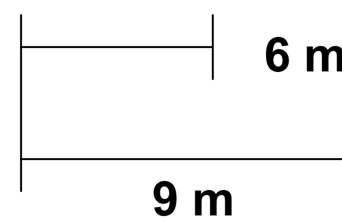
Goal: To determine whether or not it is possible to use SNO to search for sterile neutrinos

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

“CAUTION: Every year several REU students are killed.”

Sudbury Neutrino Observatory



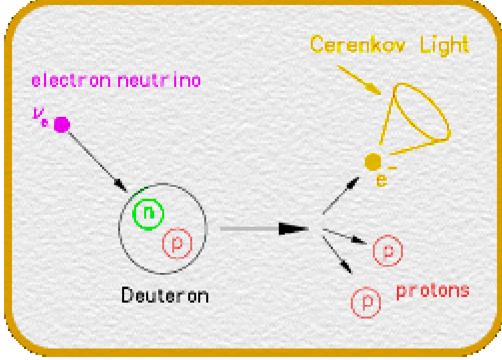


- Heavy Water Čerenkov Detector
- 2 km underground, INCO Ltd. Creighton mine
- 12 m diameter AV, filled with heavy water
- Light water extending from the AV to the edges of the SNO cavity
- 18 m diameter PMT support structure

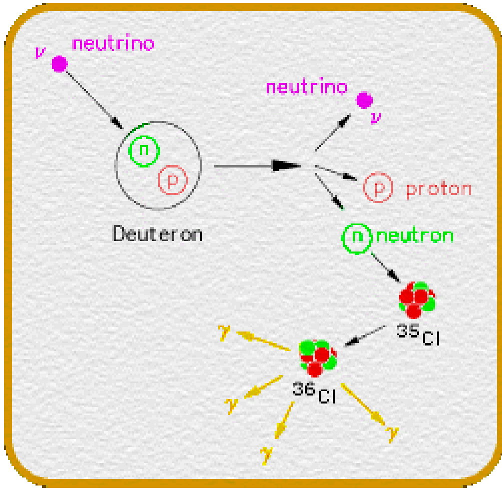
“No. Did you?”

Detection of Neutrinos

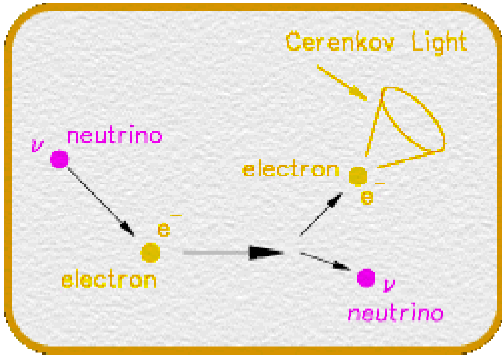
$$\nu_e + d \longrightarrow p + p + e^- \qquad (CC)$$



$$\nu_x + d \longrightarrow p + n + \nu_x \qquad (NC)$$



$$\nu_x + e^- \longrightarrow \nu_x + e^- \qquad (ES)$$



Three Phases – Heavy Water, Salt, NCD

"CORE DUMPED!"

Neutrino Oscillations

Equations? AHHHHH!

- Three flavors of neutrinos, called the "weak states" - v_e, v_μ, v_τ
- Massless in the Standard Model
- "Mass states" v_1, v_2, v_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 $\langle\nu_\mu|\nu_e(t)\rangle$:

$$P(\nu_e \rightarrow \nu_\mu) = 1 - sin^2 2\theta\, sin^2(\frac{1.27\Delta m^2 L}{E_\nu})$$

$$P(\nu_e \rightarrow \nu_e) = 1 - P(\nu_e \rightarrow \nu_\mu)$$

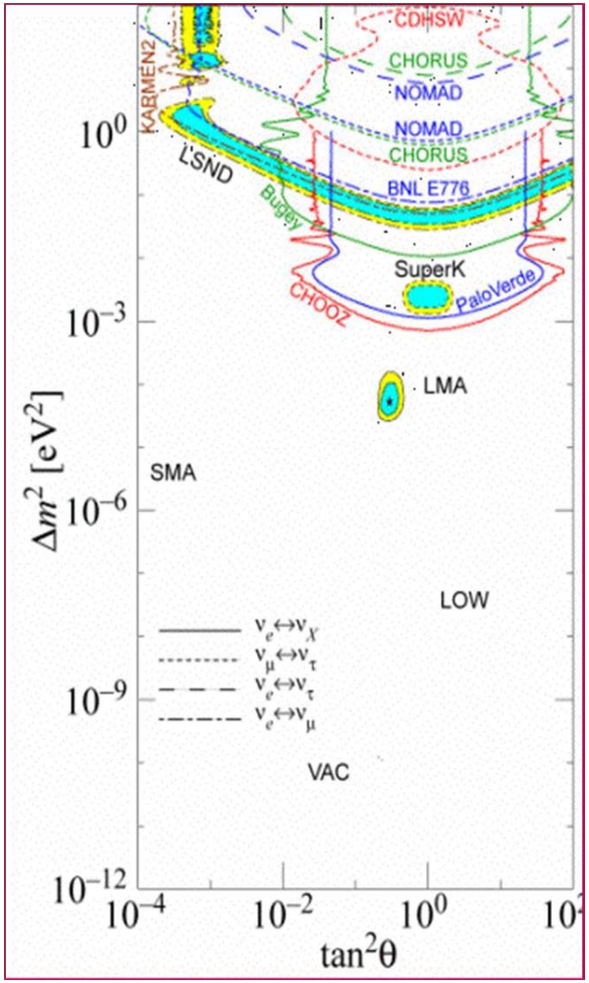
Neutrino oscillation can be understood in a very simple way. What happens is that the lighter mass states in the original v_x *travel faster than the heavier ones, and get ahead of the latter. Thus, the various* v_m components of the beam get out of phase with one another, and do not add up to a v_x *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:

$\Delta m^2_{12} < 10^{-5}$

$\Delta m^2_{23} < 10^{-3}$

$\Delta m^2_{13} > 10^{-1}$

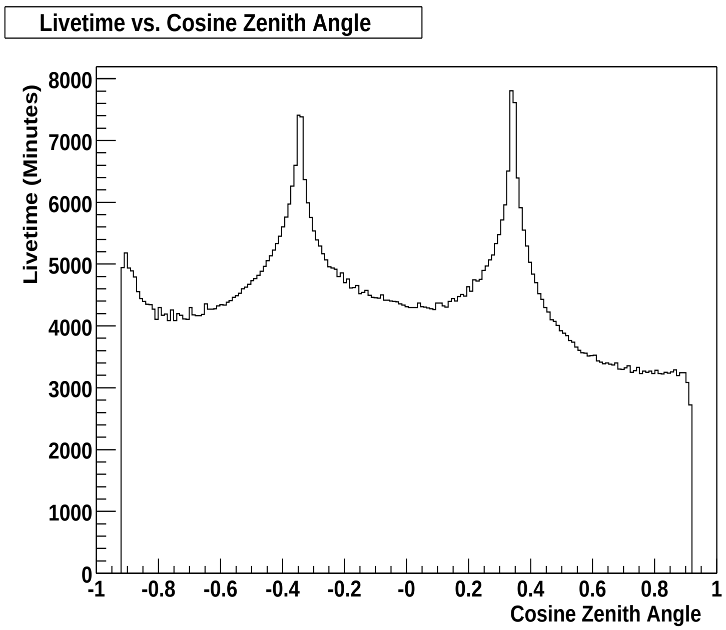
- $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$. Doesn't add up!
- Need at least one more neutrino
- LEP says there are only three active neutrinos
- Any additional neutrinos must not interact with the Z, must be sterile

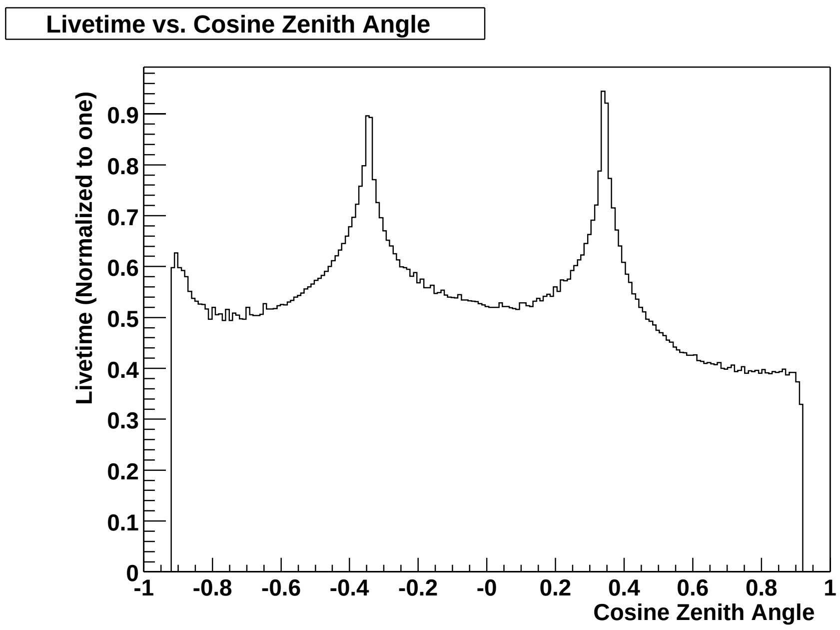
"Wheeeeeeeeeeeee!"

Detector Yield

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

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



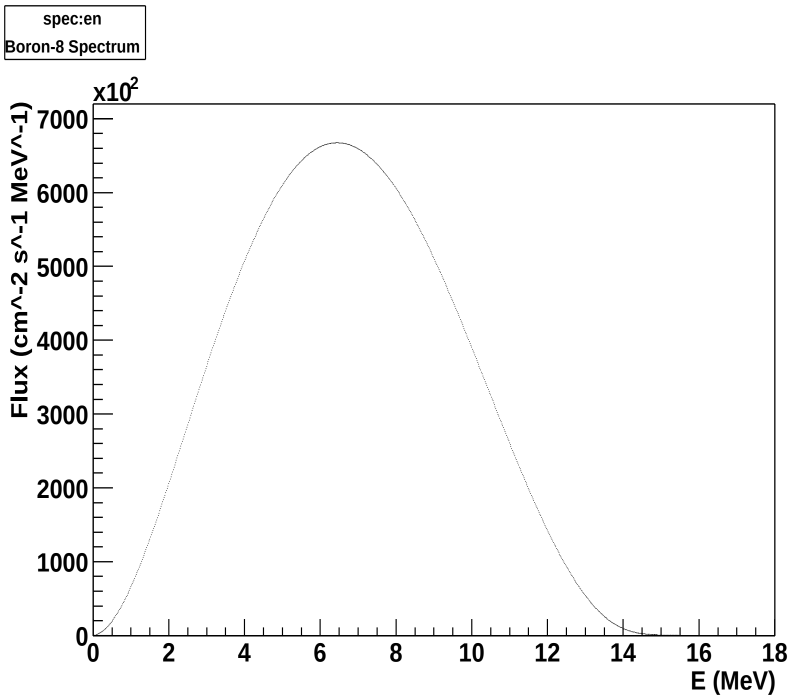


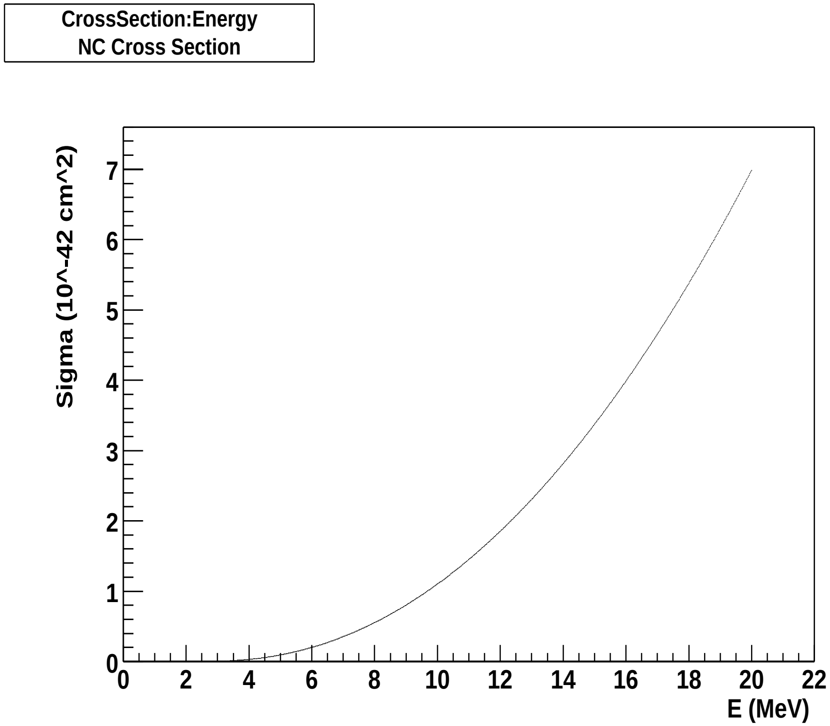
"See-worthy."

Detector Yield

Still Explaining the Big Equation

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





“Who is your Daddy, and what does he do?”

Day – Night Asymmetry

How we actually "see" the sterile neutrinos in SNO

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

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

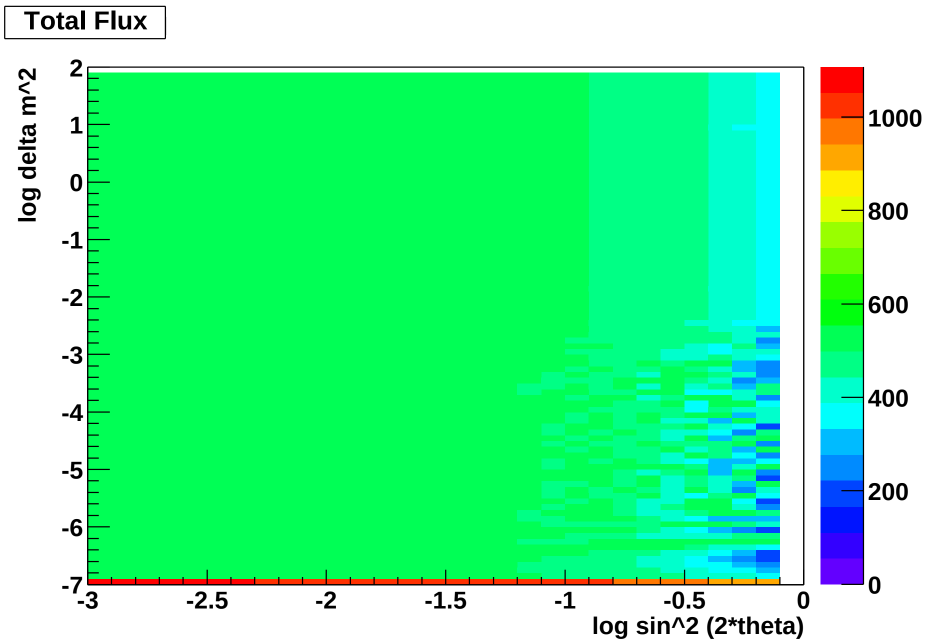
$$A = 2\,\frac{N - D}{N + D}$$

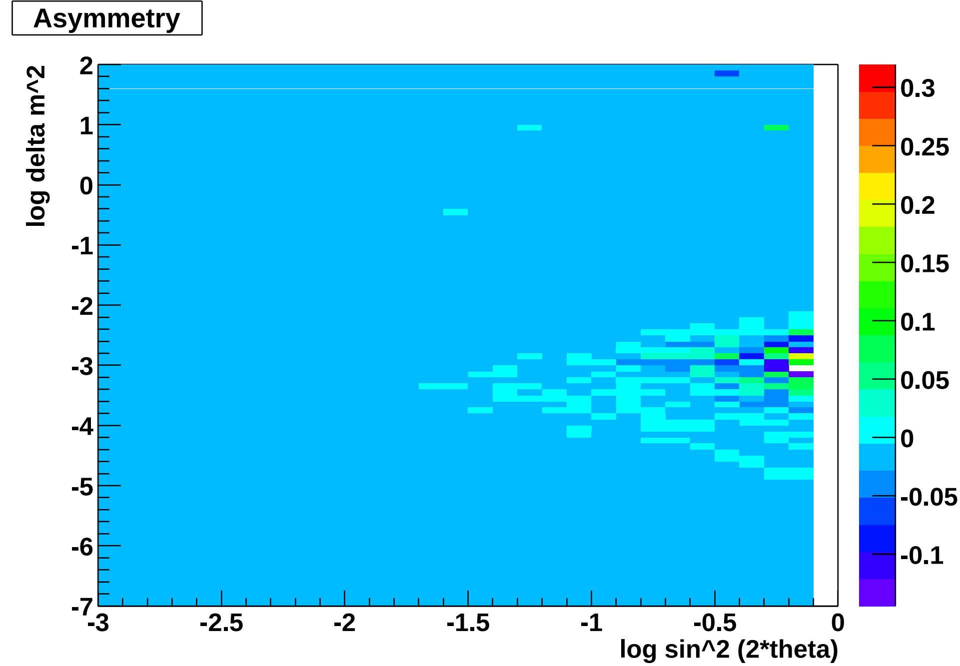
- Different values of the length of travel of the neutrino during night and day change the probability of oscillating into a sterile state
- Non-zero asymmetries should be observed if sterile neutrinos exist
- Can SNO see them?

"Jobs and Growth!"

Results

Look at the pretty graphs that I made!





$log sin^2 2\theta$, $log \Delta m^2$	Asymmetry	$\sigma_A(D_2O)$	σ_A (all phases)
-0.1, -2.2	-0.7%	10.9%	5.5%
-0.1, -2.4	14.3%	10.9%	5.4%
-0.1, -2.6	32.0%	11.3%	5.6%
-0.1, -2.8	-8.1%	9.0%	4.5%
-0.1, -3.0	13.7%	9.7%	4.9%
-0.1, -3.2	-0.6%	8.6%	4.3%
-0.1, -3.4	-11.2%	13.9%	7.0%
-0.1, -3.6	2.5%	9.0%	4.5%
-0.1, -3.8	-0.4%	8.6%	4.3%
-0.1, -4.0	-2.7%	12.4%	6.2%
-0.1, -4.2	-1.8%	13.3%	6.6%
-0.1, -4.4	-0.5%	9.2%	4.6%
-0.1, -4.6	0.4%	9.7%	4.8%
-0.1, -4.8	0.0%	8.5%	4.3%
-0.1, -5.0	0.1%	9.0%	4.5%

"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 3σ is not yet known

- Much more work is required

  Non-constant Earth-Sun Distance

  Matter effects

  Extension of σ_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

- The NSF, University of Washington, INT, CENPA
- Dr. Peter Doe, Joseph Formaggio, Kathryn Miknaitis
- Arnold Schwarzenegger
- Jon Stewart
- The Producers of T3 (for their advancements in the design of high-energy particle accelerators)
- The Voices in My Head

"I think the tide's coming in."