MUON FOLLOWERS IN THE SUDBURY NEUTRINO OBSERVATORY

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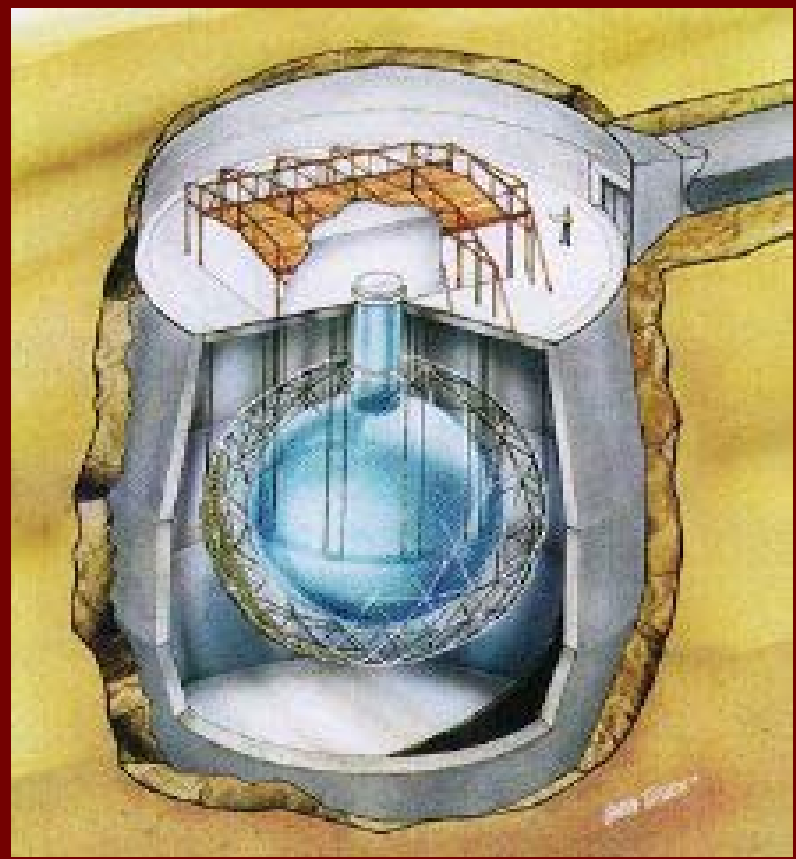
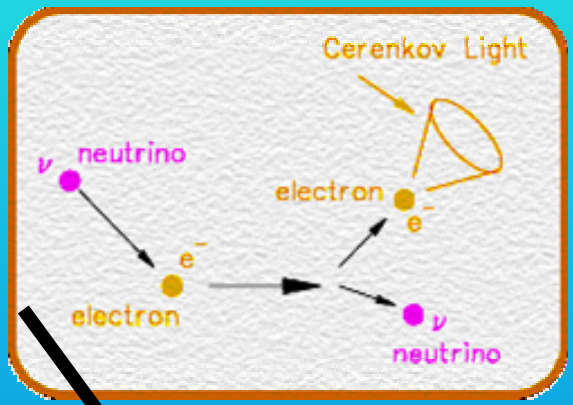
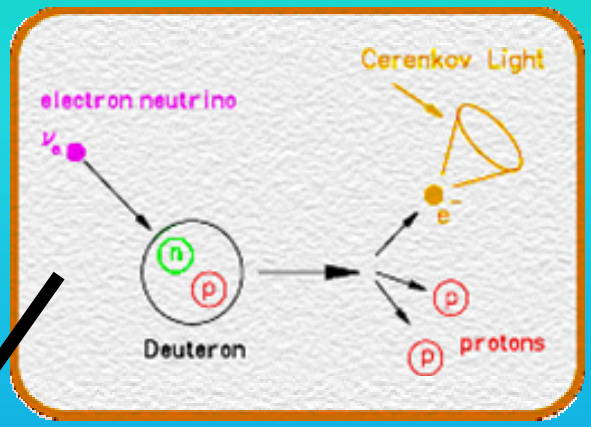
Getting to Know

- Located 2km deep underground
- Acrylic vessel 12m in diameter
- Filled with 1,000 metric tonnes (2240 lb) of ultra-pure heavy water (D_2O)
- Fully resolved the solar neutrino problem in 2002

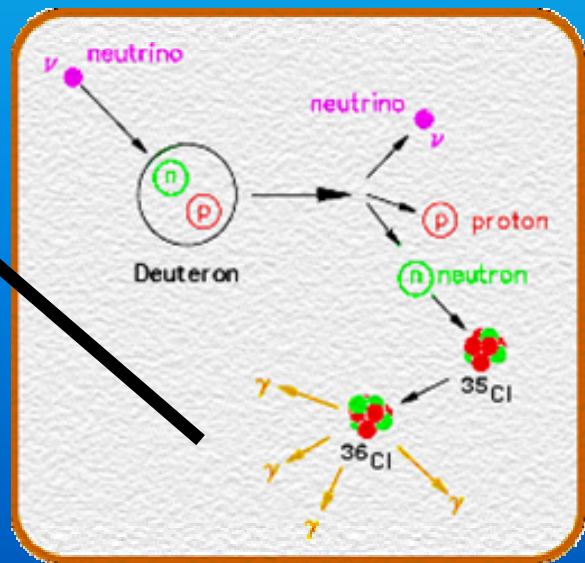


One, Two, Three Reactions





- $\nu_e + d \rightarrow e^- + p + p$ (CC)
- $\nu_x + d \rightarrow \nu_x + p + n$ (NC)
- $\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)



The Three Phases of SNO

- Pure D_2O phase
(completed June 2001)

Ingredients: ultra-pure D_2O

- Salt phase
(completed Sept. 2003)
Ingredients: add salt

- NCD phase
(in progress)
Ingredients: first, magically remove the salt, then add ^3He

And now a word on Muon Followers

What are they?

(one or more)

$$\mu + d \rightarrow \mu + n + X$$

(X is the recoil nucleus)

$$\mu + {}^{16}O \rightarrow \mu + n + X$$

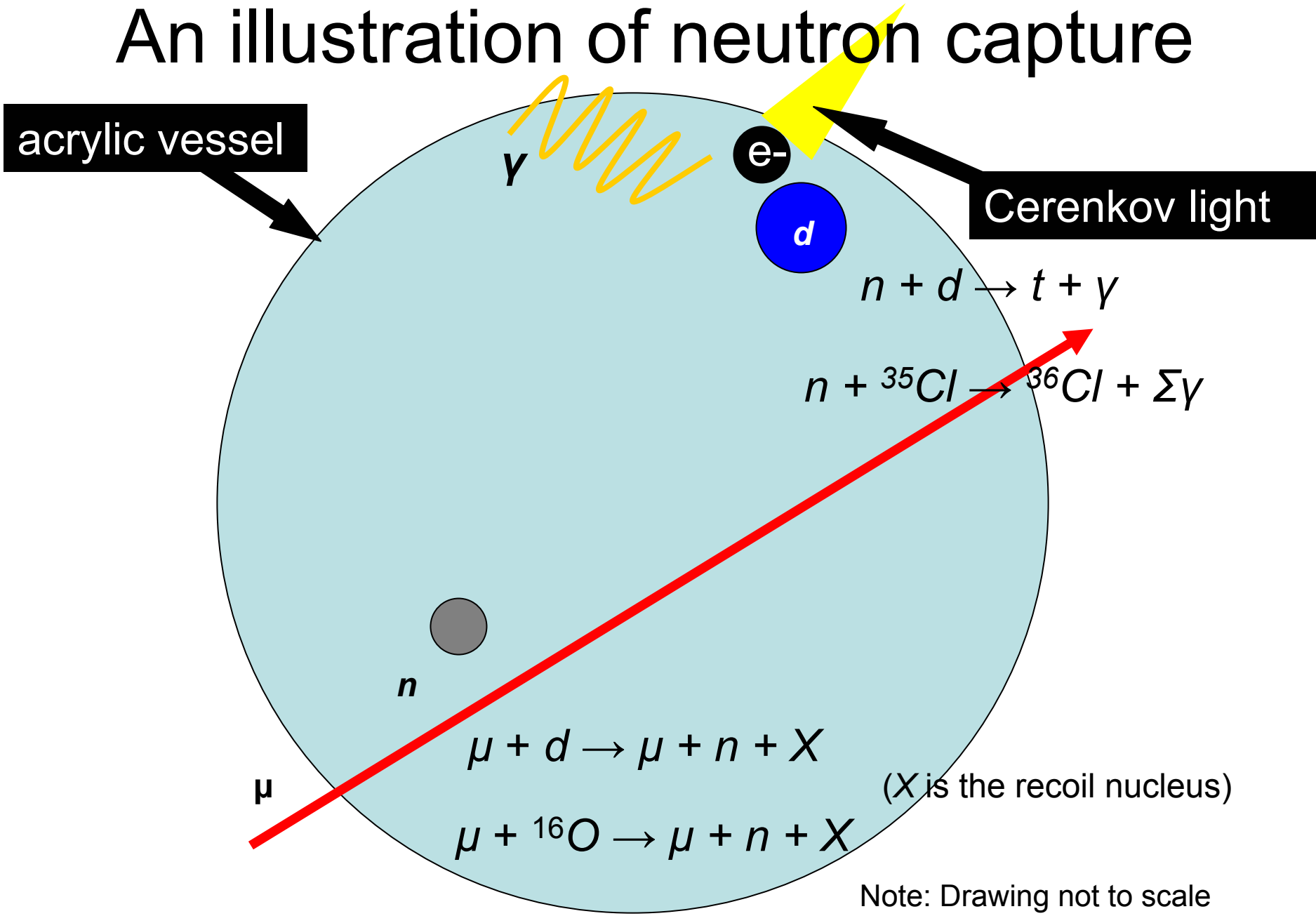
(one or more)

The goal: to determine the capture efficiency for both low and high energy neutrons as a function of radius

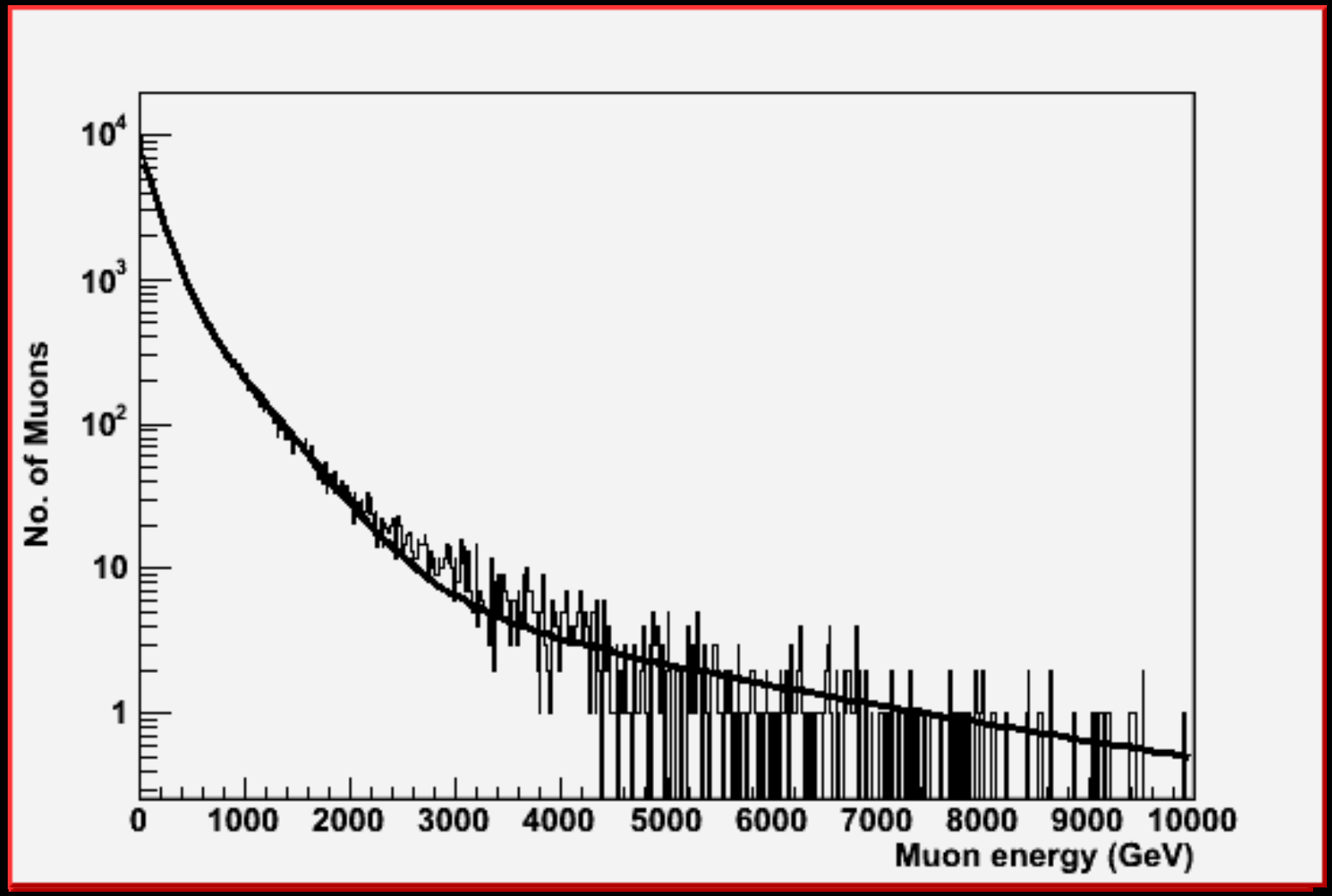
"And everywhere the muon went, the muon went, the muon went.

Everywhere the muon went, the neutron was sure to follow."

An illustration of neutron capture



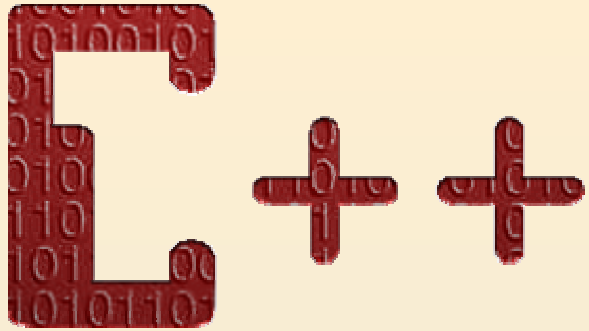
Muon Energy Spectrum



If the function fits…

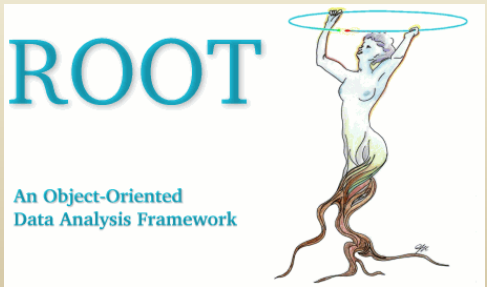
The fitting function:

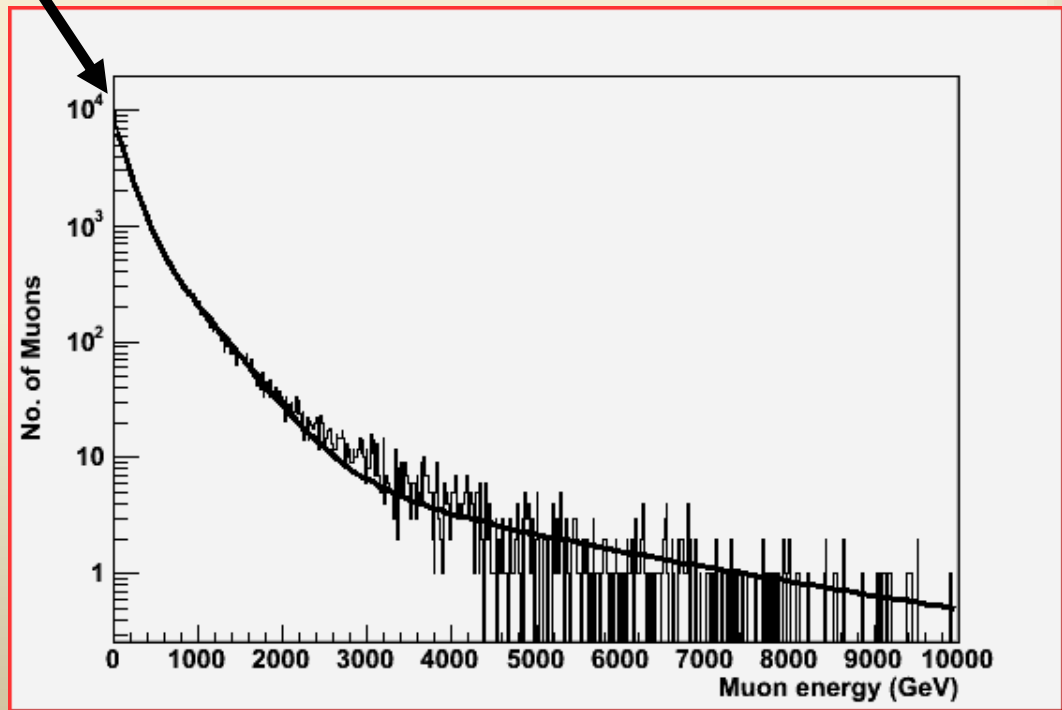
$$F(x) = ae^{-bx} / x + ce^{-dx} + fxe^{-gx}$$



with *a = 2.41231E4, b = 1.57581E-4, c = 7.69494E3, d = 2.81733E-3, f = -1.89793E1, and g = 4.23727E-3,*

provides a fit with a chi square/degree of freedom of 1.0908.





...use it

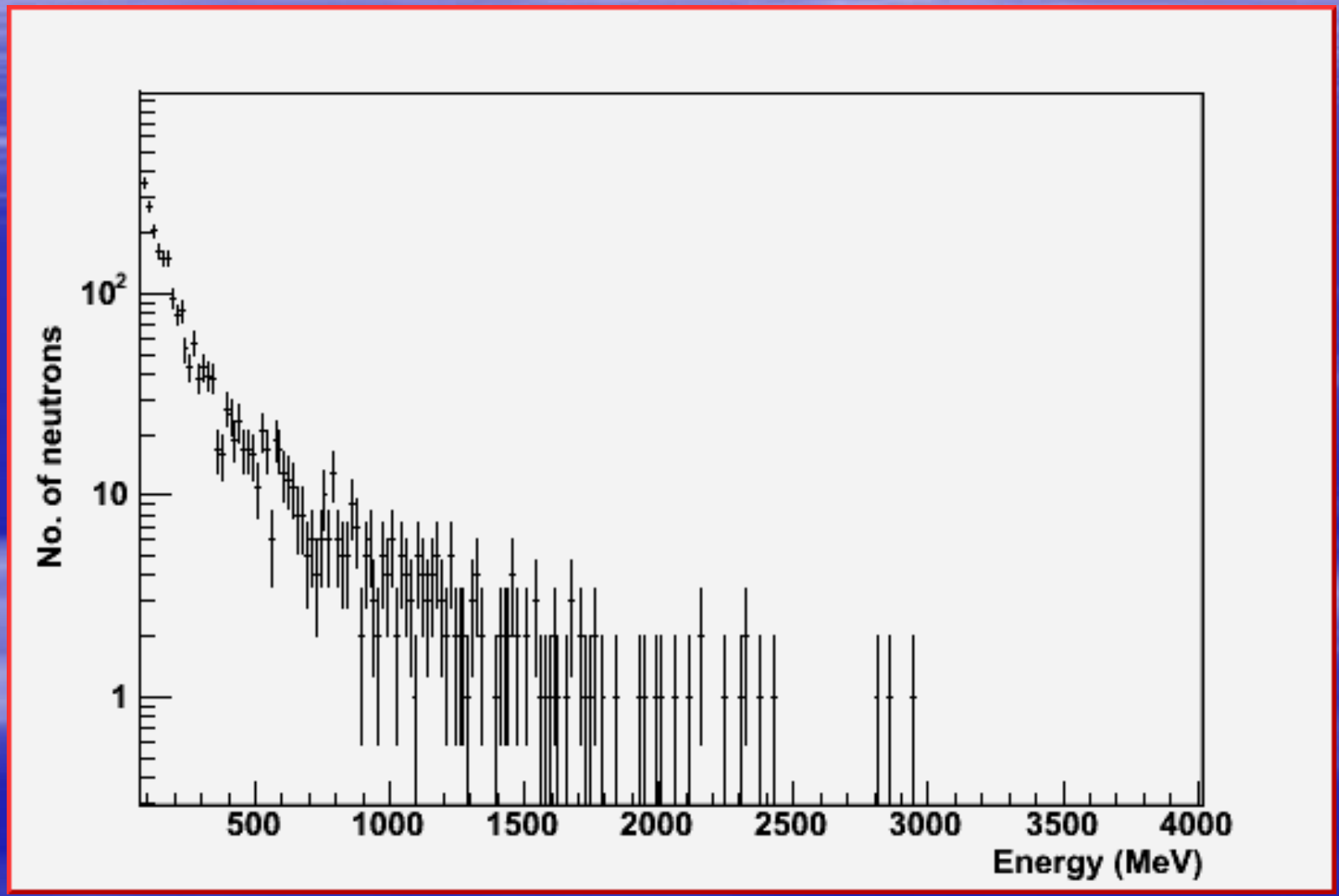
The spallation neutron energy depends on the muon energy in the following way:

$$\frac{dN}{dE_n} = A\left(\frac{e^{-7E_n}}{E_n} + B(E_\mu)e^{-2E_n}\right)$$

where A is a normalization factor, and

$$B(E_\mu) = 0.52 - 0.58e^{-0.0099E_\mu}$$

Neutron Energy Spectrum

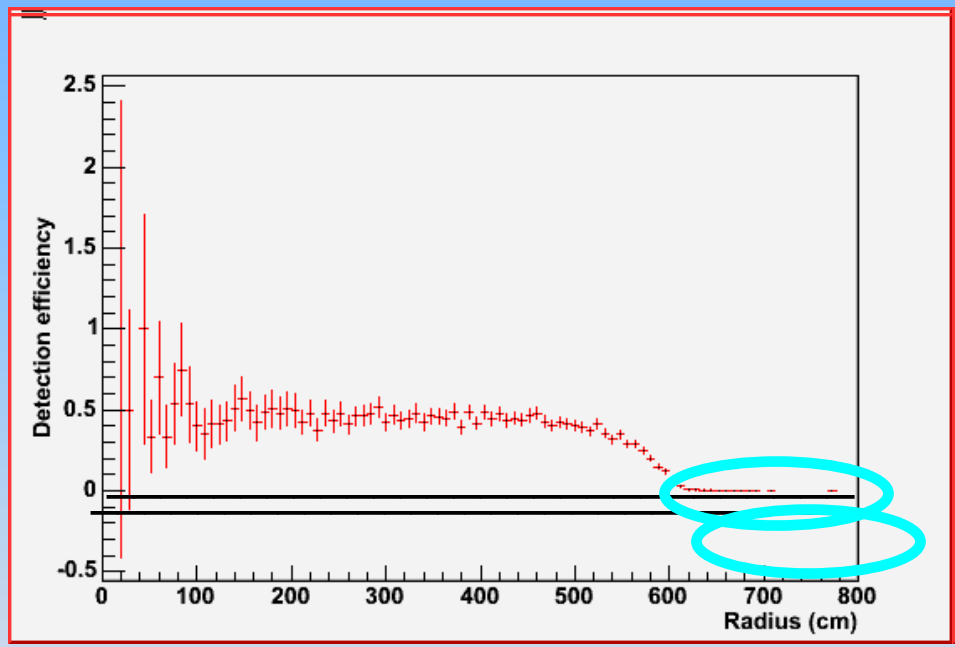


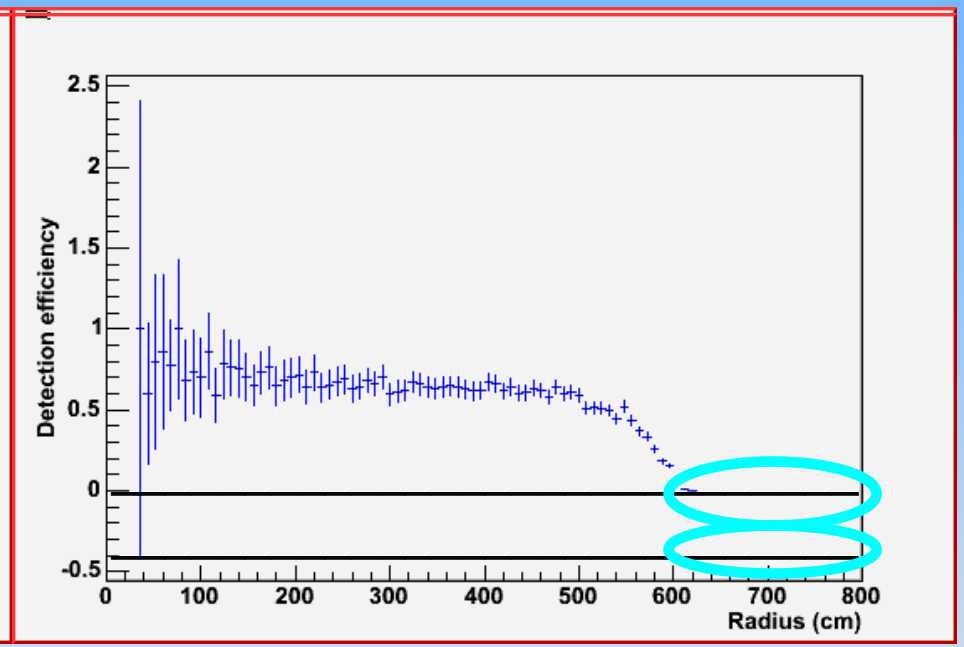
The next step

- Compare low and high energy neutrons for Pure D_2O and Salt phases
- Use SNOMAN, the SNO Monte carlo and ANalysis program, which simulates event by event in the SNO detector

From the SNOMAN companion 5.00 website

Hey neutron capture, what is your efficiency rate?





Efficiency curve for spallation neutrons in the Salted D_2O phase

Efficiency curve for low energy neutrons in the Salted D_2O phase

Fitting the efficiency curves

$$\in = \frac{\Sigma_D}{\Sigma} \mathrm{x} \{1 - F_{escape}\}$$ where

$$F_{Escape} = \frac{R}{s} \frac{\sinh(\frac{s}{l})}{\sinh(\frac{R_e}{l})} \left[\cosh(\frac{R_e - R}{l}) + \frac{l}{R} \sinh(\frac{R_e - R}{l}) \right]$$ with

$$l = \sqrt{\frac{D}{\Sigma}}$$

neutron type	parameter	value	X^2/ndf
spallation, D_2O	Σ/Σ_D l	0.355128 153.09	0.4842
low energy, D_2O	Σ/Σ_D l	0.363989 135.96	0.711
spallation, Salt	Σ/Σ_D l	0.463736 50.8892	0.3797
low energy, Salt	Σ/Σ_D l	0.670514 -57.3297	0.4245

Parameter values for R fixed.

neutron type	parameter	value	X^2/ndf
spallation, D_2O	Σ/Σ_D	0.322366	0.4485
	l	130.101	
	R	652.906	
low energy, D_2O	Σ/Σ_D	0.347964	0.7079
	l	124.802	
	R	585.625	
spallation, Salt	Σ/Σ_D	0.459867	0.3675
	l	48.8738	
	R	593.317	
low energy, Salt	Σ/Σ_D	0.659948	0.3721
	l	-50.5529	
	R	590.287	

Parameter values for R not fixed.

Why are neutron capture efficiencies important?

- It will enable us to measure the rate of neutrons released as each muon passes through

- One of the dominant backgrounds for many sensitive underground experiments remains neutrons induced by high energy cosmic rays

SUMMARY

- Muons and muon followers with the proper energy distributions produced

- Capture efficiencies for spallation and low energy neutrons have been produced and parameterized

- They have been compared for both the Pure D_2O and Salt phases of SNO using an isotropic volume neutron source

- The relative efficiencies have been tested using a point neutron source at the center

- Further investigation on the absolute efficiencies

Acknowledgements

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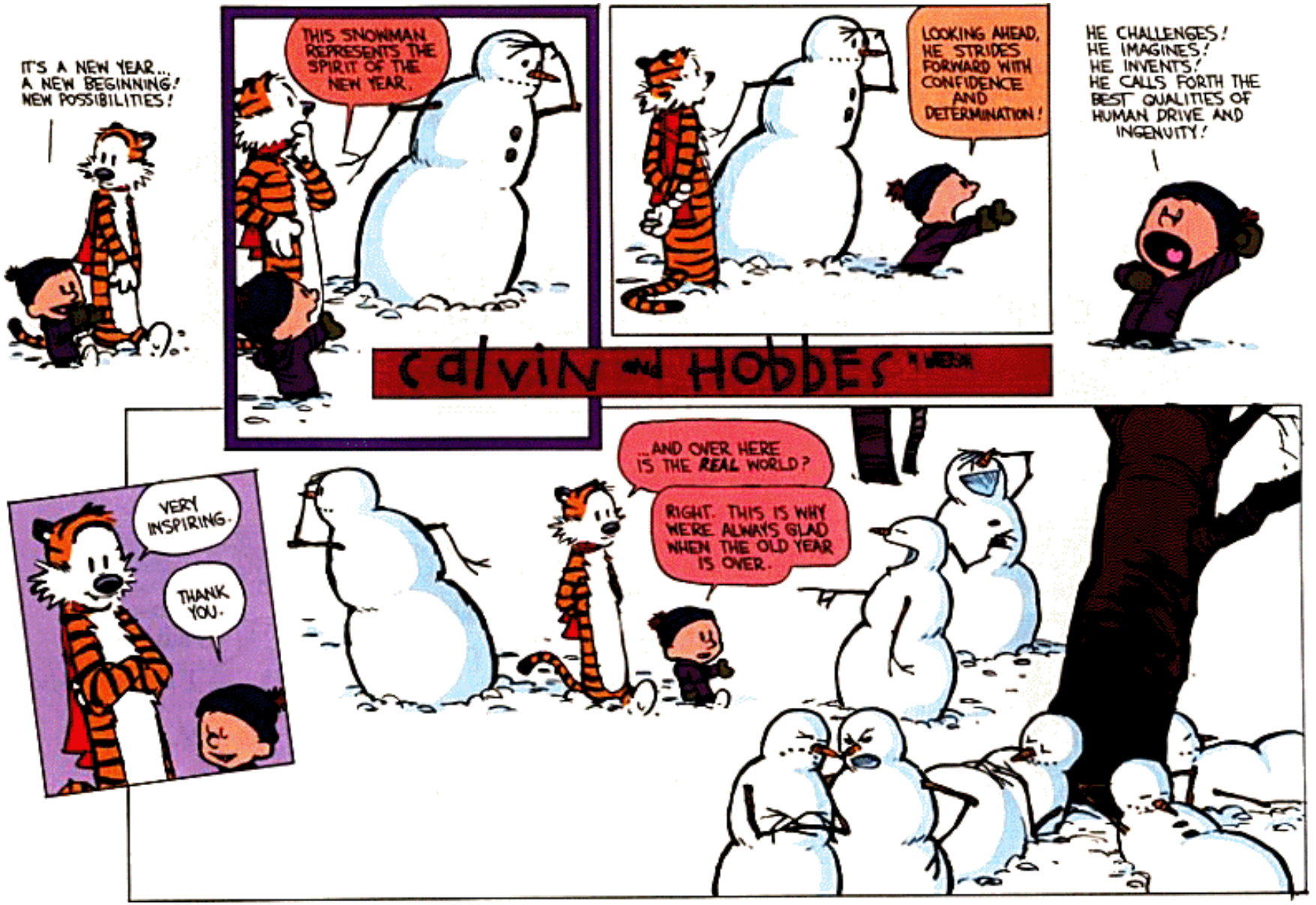
- The NSF and the UW REU Program
- The 2004 UW REU students

THE END


IT'S A NEW YEAR... A NEW BEGINNING! NEW POSSIBILITIES!
THIS SNOWMAN REPRESENTS THE SPIRIT OF THE NEW YEAR.
LOOKING AHEAD, HE STRIDES FORWARD WITH CONFIDENCE AND DETERMINATION!
HE CHALLENGES! HE IMAGINES! HE INVENTS! HE CALLS FORTH THE BEST QUALITIES OF HUMAN DRIVE AND INGENUITY!
Calvin and Hobbes
VERY INSPIRING.
THANK YOU.
...AND OVER HERE IS THE REAL WORLD?
RIGHT. THIS IS WHY WE'RE ALWAYS GLAD WHEN THE OLD YEAR IS OVER.