1000 tonnes D$_2$O
12 m diameter Acrylic Vessel
18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)
1700 tonnes inner shielding H$_2$O
5300 tonnes outer shielding H$_2$O
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day
The End of SNO Heavy Water

- the Sudbury Neutrino Observatory finished taking data with heavy water
- heavy water was drained and returned to Atomic Energy of Canada Limited
  - Nov 28, 2006
    - end of data taking and detector turned off
  - Jan 18, 2007
    - last NCD taken out
  - Jan 27, 2007
    - began removing D$_2$O from the neck
  - May 28, 2007
    - AV completely drained
      - using a submersible pump
      - plus entry into the AV using a bosun’s chair
      - used pump hose to vacuum up the last D$_2$O
      - used pipette to get last ~200 mL

- what can we fill the detector with next?
SNO+

- We plan to fill the SNO detector with a liquid scintillator (50-100 times more light)
- Linear alkylbenzene (LAB)
  - Compatible with acrylic, undiluted
  - High light yield, long attenuation length
  - Safe: high flash point, low toxicity
  - Cheaper than other scintillators

LAB is a commodity chemical used to make the surfactant in common, household detergents
SNO+ Physics Program

- search for neutrinoless double beta decay
- neutrino physics
  - solar neutrinos
  - geo antineutrinos
  - reactor antineutrinos
  - supernova neutrinos

SNO+ Physics Goals
Draining SNO and Boating Inspections
Inside the SNO AV Looking Out
SNO Cavity Drained, Inspected
Geoneutrino Detection

- A geoneutrino interacts with a proton in the detector
  - A few times per month
- The positron plus its annihilation gamma rays produce a flash of light (prompt signal)
- The neutron thermalizes and captures on another proton with mean lifetime 0.2 ms, producing a gamma ray of 2.2 MeV and a second flash of light (delayed signal)
- Photomultiplier tubes measure the amount of light and time they were hit
  - Allows reconstruction of the energy and position of the neutrino interaction
  - Don’t have information about the neutrino direction… the neutron is forward scattered, but wanders while thermalizing; plus 2.2 MeV gamma ray scintillation is displaced another few cm’s

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Geoneutrinos in SNO+

- KamLAND: 33 events per year (1000 tons CH₂) / 142 events reactor
- SNO+: 44 events per year (1000 tons CH₂) / 38 events reactor

SNO+ geo-neutrinos and reactor background

KamLAND geo-neutrino detection…July 28, 2005 in Nature
LAB is mostly approximately $C_{18}H_{30}$

- more like 29 events per year
  - fiducial volume cut? 80%
  - livetime fraction? 75%
  - efficiency (high, depends on fiducial cut)

- so it will be $\sim$20 events per calendar year
Geo-$\nu$ from Continental Crust

Fraction of Geo-Neutrino Signal

- crust: blue
- mantle: black
- total: red

in SNO+
SNO+ Geoscience Goals

- test fundamental models of Earth’s chemical origin
  - are measured fluxes consistent with predictions based upon the BSE?
  - so far yes, KamLAND 2008 measurement central value equals the BSE predicted flux
- test chemical composition of the crust
  - are the basic ideas about the makeup and distribution of elements in continental crust correct?
- with detailed local contribution study, can study the 20% deep Earth component
- global program: SNO+ and Hanohano would be a terrific combination
Steps Required

- build/install hold down for acrylic vessel [~$2M]
- procure liquid scintillator and components [~$2M]
- build/install scintillator purification [~$7M]
- upgrade cover gas and detector interface (glove box) [$0.35M]
- minor upgrades to electronics/DAQ [$0.2M]
- build calibration systems for [$0.3M]
SNO+ Hold Down Net

rope tension calculation as input for finite element analysis and for PSUP penetration geometry
AV Hold Down

- FEA stress and buckling calculations completed
Scintillator Purification
Solar Neutrinos at Low Energy

- $^8\text{B}$ solar $\nu$ well studied
  - Super-K and SNO
- there are good data on $pp$ solar $\nu$'s from SAGE, Gallex and GNO
  - must determine contribution of $^8\text{B}$ and $^7\text{Be}$, subtract, and you get $pp$ from the Ga experiments
- Borexino and KamLAND will be studying $^7\text{Be}$

...$pp$ and $CNO$ solar neutrinos are next
SNO+ pep Solar Neutrino Signal

Simulated SNO+ Energy Spectrum

3600 pep events/(kton·year), for electron recoils >0.8 MeV
Background from $^{11}\text{C}$ Eliminated

- SNO+ is at 6000 m.w.e. depth
  - muon flux reduced a factor 800 compared to Kamioka and a factor 100 compared to Gran Sasso
  - recall KamLAND’s post-purification goal

KamLAND and Borexino will try to tag and veto the $^{11}\text{C}$ to suppress at SNO+ depth this background is already smaller than the signal and one can still tag and veto
Survival Probability for Solar Neutrinos: All Experimental Data Distilled

\[ \Delta m^2 = 8.0 \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 \theta = 0.31 \]

From SNO CC/NC = 0.34 ± 0.04

Figure from TAUP 2007 (pre-Borexino 2008)
What is Double Beta Decay?

- some nuclei cannot $\beta$ decay but can undergo double beta decay, a very rare process
  - e.g. $^{76}\text{Ge}$ has half-life $1.3 \times 10^{21}$ years

- even rarer is neutrinoless double beta decay (has never been observed...well sort of never!)

![Diagram of double beta decay]

\[2\nu\beta\beta\]
What is Double Beta Decay?

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Diagram:
- Mass vs. Z, atomic number.
- ββ decay path.
- 0νββ decay path, requires neutrino to be its own antiparticle – Majorana.
SNO+ Double Beta Decay

- ...sometimes referred to as SNO++
- it is possible to add $\beta\beta$ isotopes to liquid scintillator, for example
  - dissolve Xe gas
  - organometallic chemistry (Nd, Se, Te)
  - dispersion of nanoparticles (Nd$_2$O$_3$, TeO$_2$)
- we researched these options and decided that the best isotope and technique is to make a Nd-loaded liquid scintillator
Why $^{150}$Nd?

- 3.37 MeV endpoint (2nd highest of all $\beta\beta$ isotopes)
  - above most backgrounds from natural radioactivity
- largest phase space factor of all $\beta\beta$ isotopes
  - and favourable nuclear matrix element
  - for the same effective Majorana neutrino mass, the $0\nu\beta\beta$ rate in $^{150}$Nd is fastest
- isotopic abundance 5.6%
  - 1% natural Nd-loaded liquid scintillator in SNO+ has 560 kg of $^{150}$Nd compared to 37 g in NEMO-III
- cost $\text{NdCl}_3$ is $86,000$ for 1 tonne
- upcoming experiments use Ge, Xe, Te; Cd and Se proposed…we can deploy a large amount of Nd
0νββ Signal for $<m_\nu> = 0.150$ eV

0ν: 1000 events per year with 1% natural Nd-loaded liquid scintillator in SNO++

The Simulated Spectrum of Double Beta Decay Events

Simulation: one year of data
$^{150}$Nd SNO+ Summary

- stable Nd-loaded liquid scintillator
- scintillation optical properties studied
- target background levels achievable with our purification techniques
- physics sensitivity may be first to reach below 100 meV (using natural Nd)
- leading sensitivity down to 40 meV (using enriched Nd)
- thus, SNO+ plans to deploy 0.1% natural Nd-loaded liquid scintillator for the first phase
List of R&D Developments for SNO+

- developed the use of linear alkylbenzene as a solvent for large liquid scintillator detectors
  - high flash point, low toxicity, high light yield, long transmission length, inexpensive!
- developed Nd-loaded liquid scintillator (using same technique as for In, Gd loading)
- developed purification techniques to remove Ra, Th from Nd and Nd liquid scintillator
- physics potential: pep and CNO solar neutrinos, geoneutrino continental crust probe, double beta with Nd in liquid scintillator
SNO+ Project Status

- was funded by NSERC for R&D in 2005-2007; funded for continued development, engineering and transition activities in 2007-2008
- initial capital funding from NSERC for 2008-2010
- submission of full capital proposal to CFI in Q4 2008
- installation of hold-down net begins in Q2 2009
- installation of scintillator process and purification begins in Q2 2010
- end of 2010 → ready for scintillator filling
SNO+ Collaboration

University of Alberta:
R. Hakobyan, A. Hallin, M. Hedayatipoor, C. Krauss, C. Ng

Brookhaven National Laboratory:
R. Hahn, Y. Williamson, M. Yeh

Idaho National Laboratory:
J. Baker

Idaho State University:
J. Heise, K. Keeter, J. Poppe, C. Taylor

Laurentian University:
E.D. Hallman, S. Korte, A. Labelle, C. Virtue

LIP Lisbon:
S. Andringa, N. Barros, J. Maneira

Oxford University:
S. Biller, N. Jelley, P. Jones, J. Wilson-Hawke

University of Pennsylvania:
E. Beier, H. Deng, W.J. Heintzelman, J. Klein, G. Orebi Gann, J. Secrest, T. Sokhair

Queen's University:
E. Beier, M. Chen, X. Dai, E. Guillian, P.J. Harvey, C. Kraus, X. Liu, J. McDonald, H.O’Keeffe, P. Skensved, A. Wright

SNOLAB:
B. Cleveland, F. Duncan, R. Ford, C.J. Jillings, I. Lawson

University of Sussex:
E. Falk-Harris, S. Peeters

Dresden University of Technology:
K. Zuber

University of Washington:
M. Howe, K. Schnorr, N. Tolich, J. Wilkerson