The SNO+ Experiment

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Student presentation      TRIUMF      April 10, 2013
The SNO experiment
SNO(+) detector
SNO+ Physics goals
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The SNO Experiment

Solved the Solar Neutrino Problem

which answered an age-old question

How does the sun shine?

which is about the same as asking

How old is the sun?

Consider:

• can easily compute the sun’s rate of energy output
• rate \times age = total energy radiated

The larger the total energy radiated (i.e. the older the sun) the harder it is to find an explanation of the source of energy.
19th Century physicists thought gravity was involved

- 1854 – Helmholtz: gravitational infall energy was being converted to heat

- 1854 – Kelvin: impact of meteors provided the heat (but it was later later shown there weren’t enough meteors in the solar system)

- 1854 – Kelvin again: so then he proposed it was primordial meteors that had provided the energy

- 1862 – Kelvin once more: “... some form of meteoric theory is certainly true ...”

  - “No other natural explanation ... can be conceived.”
  - chemical processes would only generate 3,000 years’ heat
  - “... no difficulty in accounting for 20,000,000 years’ heat ...”
Other 19th Century scientists thought the earth (hence the sun) was much older.

Hutton – 1788: from geologic considerations, “... we find no vestige of a beginning, – no prospect of an end.”

Lyell – 1830: published Principles of Geology. Extended Hutton’s idea of uniformitarianism: same geologic processes operating now as in the past, and at the same rate

Phillips – 1841: published the first global geologic time scale. Estimated earth’s age as 96,000,000 years.

Darwin – 1859: Origin of Species published. Estimated age to be 300,000,000 years by considering erosion of earth’s features.
How does the Sun shine?

The first breakthrough came in 1896 when Becquerel discovered radioactivity.

1903: P. Curie and A. Laborde showed radium released heat without cooling down, thus establishing a previously unknown source of energy.

1904: Rutherford found alpha particle radiation indeed released enormous amounts of energy. The Sun could have been around for a long time if this was the source of its energy.

Thus the disagreement between physicists and other scientists as to the age of the earth was beginning to be resolved. Unfortunately, observations of the Sun showed it contained mostly hydrogen and not much radioactivity.
How does the Sun shine?

The question resolved...

1905: Einstein showed the equivalence of mass and energy \((E=mc^2)\). Hence a small amount of mass could be converted to a large amount of energy.

1920: Aston showed that four hydrogen nuclei were heavier than a helium nucleus.

Eddington then suggested the Sun could shine by converting four hydrogen nuclei to helium.

But classically, even two hydrogen nuclei can never come together.

1925: Heisenberg and Schrödinger independently invent Quantum Mechanics.

1928: Gamow showed in QM how two like-charged particles can overcome the electrostatic repulsion between them.

1938: Bethe introduced the p-p chain of nuclear reactions.
Thus four protons are converted to helium with the release of two neutrinos.
Detection thresholds for the various experiments

Neutrino Flux

Neutrino Energy (MeV)

Gallium  Chlorine  SuperK, SNO
The Solar Neutrino Problem

Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(OP)]

In all cases fewer neutrinos are detected than predicted.
The SNO Experiment

Previous experiments could only measure electron neutrinos. SNO was designed to measure all flavours using heavy water (D$_2$O) as a target.

**D$_2$O Detection Reactions**

**CC** \( \nu_e + d \rightarrow p + p + e^- \)
- spectral shape (distortion \(\Rightarrow\) oscillations)
- directional sensitivity \( W(\theta) \sim 1 - \frac{1}{3} \cos(\theta) \)

**NC** \( \nu_x + d \rightarrow \nu_x + p + n \) flavor blind!
- capture \( n \) on \( D \) or \( Cl \) and see \( \gamma \)s, or
- detect \( n \) in \(^3\)He counters
- measures total \(^8\)B solar \( \nu \) flux above 2.2 MeV
- stellar collapse - observe \( \nu_e, \nu_\mu, \nu_\tau \)

\[
\frac{CC}{NC} = \frac{\nu_e \text{ flux}}{(\nu_e + \nu_\mu + \nu_\tau) \text{ flux}}
\]

**ES** \( \nu_x + e^- \rightarrow \nu_x + e^- \)
- directional sensitivity (strongly forward peaked)

\[
\frac{CC}{ES} = \frac{\nu_e \text{ flux}}{\nu_e + 0.15 (\nu_\mu + \nu_\tau) \text{ flux}}
\]

\( \bar{\nu}_e + d \rightarrow n + n + e^+ \)
- unique signature for \( \bar{\nu}_e \)s
Acrylic Vessel - 12 m diameter

Heavy water - 1000 t D₂O

Phototube sphere - ~ 9500 PMTs

Water shielding - 1700 t inner
- 5300 t outer

Urylon liner - radon seal

Deep underground lab
AV and Phototubes
Phototube support structure
SNO Čerenkov Events

Neutrino event

- actual ring position
- sinusoidal view rotated
- PMT location view
- PMT hit times

Muon event
SNO showed that the discrepancy between theory and experiment in the older experiments was because they were not measuring the total neutrino flux – the result of neutrino flavour change (oscillations).
Vale’s Creighton Mine

Acrylic Vessel
- 12 m diameter

Liquid scintillator
- 780 t LAB

Phototube sphere
- ~ 9500 PMTs

Water shielding
- 1700 t inner
- 5300 t outer

Urylon liner
- radon seal

Deep underground lab

SNO+ Detector

Already exists!
The scintillator cocktail of choice is Linear Alkylbenzene (LAB) with 2g/L of PPO

- developed by SNO+ collaborators (Queen’s)
- chemically compatible with acrylic
- high flash point, low toxicity – SAFE!
- large light output – expect > 400 hits/MeV (9 hits/MeV in SNO)
- readily available – LAB is used in the production of detergents
- made in Canada, plant is < 700 km from SNOLAB
- Petresa LAB has the best optical quality of all the LABs SNO+ tested.
- Petresa willing to carry out special steps for SNO+
  - purge all process lines and vessels with boil-off N₂
  - flush with N₂ and dedicate all delivery trucks
- concentration of 2g/L PPO gives emitted light a wavelength distribution that matches the PMT response.
Scintillator Properties

Timing properties of the LAB-PPO scintillator were measured in a simple bench top experiment - see NIM A640 (2011) 119.

Effect of deoxygenating the scintillator on the timing spectra for alphas and electrons.

Ratio of a short time integration window over the peak of each event divided by a long time integration.

These data show the deoxygenated scintillator exhibits slightly better alpha/electron separation, and that it is possible to retain > 99.9% of the electrons while rejecting > 99.9% of the alphas.
A separate measurement showed LAB light output is linear with energy [see NIM A654 (2011) 318]

The refractive index has also been measured. [see Phys. Scripta 03 (2011) 035701].
SNO+ gains from the experiences of:
- Borexino (achieved better than SNO+ goals) and
- KamLAND (developed successful purification techniques)
- SNO+ uses the same construction, purification techniques and materials as Borexino, hence
  - should achieve same background levels

The target levels are:
- Th: $10^{-17}$ g/g ($\sim$ 3 cpd for $^{208}$Tl and $^{228}$Ac)
- U: $10^{-17}$ g/g ($\sim$ 9 cpd for $^{210}$, $^{214}$Bi)
- $^{40}$K: $1.3 \times 10^{-18}$ g/g ($\sim$ 23 cpd)
- $^{85}$Kr, $^{39}$Ar: < 100 cpd

To achieve these goals the purification steps include:
- multistage distillation (removes heavy metals, improves UV transparency)
- $N_2$/water vapour gas stripping using a packed gas stripping tower (removes Rn, Kr, Ar, O$_2$)
- water extraction (removes K, Ra, Bi)
- metal scavenging (removes Ra, Bi, Pb; also can be used to assay $^{210}$Bi, $^{210}$Pb - useful when looking for CNO neutrinos)
- microfiltration
Physics Program

Search for neutrinoless $\beta\beta$-decay
(highest priority for SNO+)

Solar neutrinos:
- precise measurement of pep survival probability
- CNO and $^8B$ neutrinos

Reactor neutrinos:
- several reactors contribute to oscillations

Geo neutrinos:
- Th, U distributions in earth’s crust

Supernova neutrinos:
- hundreds of events
Neutrinoless $\beta\beta$-decay

Ordinary $\beta$-decay:
A neutron transforms into a proton and an electron and electron antineutrino are emitted.

Two neutrino double beta-decay ($2\nu\beta\beta$):
Two neutrons in the same nucleus transform at the same time.

Zero neutrino double beta-decay ($0\nu\beta\beta$):
The antineutrino emitted at the first vertex is absorbed as a neutrino at the second.
The search for neutrinoless $\beta\beta$-decay is a high priority within the community to:

- establish whether neutrinos are Dirac or Majorana particles
- probe neutrino masses at the level of tens of meV

$^{150}$Nd is an excellent candidate:

- has the largest phase space factor - 33 x larger than $^{76}$Ge
- has the second largest Q-value – above most backgrounds from natural radioactivity
- for the same effective Majorana neutrino mass, $0\nu\beta\beta$ in $^{150}$Nd has the fastest calculated rate
- 1% Nd-loaded LAB has been stable over several years
- self-scavenge pH-controlled purification is effective at removing Th and other radioisotopes [see NIM A618 (2010) 124] and optical transmission is improved
How much Nd?

Although 1% loading is stable, there is too little light.

Default loading is 0.1% (43.6 kg of $^{150}$Nd)

But optimization studies suggest 0.3% loading might be a better compromise between light output and statistics.

So slowly increase the Nd concentration – Nd signal and background will increase but detector backgrounds will stay the same.
**Neutrinoless $\beta\beta$-decay**

$\beta\beta$-decay signal for 0.1% Nd loaded scintillator

- ~ 2 years live time
- $^{214}$Bi can be tagged by $\beta^-$ - $\alpha$ coincidence and removed
- constrain $^{208}$Tl with $^{212}$Bi → $^{212}$Po delayed $\beta^-$ - $\alpha$ coincidence

**Neutrino mass sensitivity for 0.3% Nd loading.**

- IBM-2 [Phys. Rev. C 79 (2009) 044301] nuclear m.e. values for Nd were used
- radioactivity backgrounds at the levels achieved by Borexino
- cosmogenic backgrounds included; pile-up under study
The $^{130}$Te option

Several big advantages to using tellurium:
- isotopic abundance is 34.5% compared with 5.6% for neodymium
- rate of $2v\beta\beta$ is two orders of magnitude less in tellurium
- dominant backgrounds do not scale with amount of isotope
- might be possible to go to much higher loadings

Some disadvantages too:
- lower Q-value, internal backgrounds will be more difficult to handle
- fiducial volume must be smaller to cut out external backgrounds

Conclusion from studies so far – provided the backgrounds can be handled, the discovery potential with tellurium is higher than with neodymium. Thus tellurium has become the default option.
Solar pep Neutrinos

The flux of pep neutrinos is a fundamental quantity in the Standard Solar Model.

Solar neutrino oscillations are governed by vacuum effects at pp energies and by matter effects at $^8$B energies.

Transition region between is fertile ground:
- just to observe the shift
- to look for nonstandard interactions.

The pep line lies nicely in this region.

The Borexino Collaboration recently announced the first observation of pep neutrinos. The measured rate was $3.1 \pm 0.6\text{(stat)} \pm 0.3\text{(syst)}$ counts/(day x 100 t).

So what can SNO+ do?

Chiavarra at PIC2011, see also arXiv:1110.3230
Solar pep Neutrinos

Main background to the Borexino pep measurement is the high rate of decay of cosmogenically produced $^{11}\text{C}$. Analysis cuts reduce this rate to a manageable level, but at a cost of half the rate of good events.

A reminder
Gran Sasso is at a depth of 3000 mwe compared with SNOLAB at 6000 mwe. SNO+ is deep! – many fewer muons.

SNO+ has lower background and larger size – can make a precision measurement. Spectra were analytically generated for one year exposure, with $5%/\sqrt{E}$ resolution, 400 t fid. vol. Other backgrounds not shown.
Solar pep Neutrinos

Simulation of the impact of SNO+ pep measurement

Energy range 0.2 - 6.5 MeV, 50% fid. vol.
Assumes $\tan^2 \theta_{12} = 0.468$
$\Delta m^2_{12} = 6.02 \times 10^{-5} \text{ eV}^2$
$\sin^2 \theta_{13} = 0.01$

Does not include latest Borexino results or large $\theta_{13}$

Tightens bound on $\tan^2 \theta_{12}$
Improves $\theta_{13}$ constraints
Solar CNO Neutrinos

A recent downward revision of solar metal abundances from solar surface measurements has led to

- better agreement with heavy element abundances in the interstellar medium
- but poorer agreement with helioseismology data

Solar model predicted CNO fluxes are greatly affected by solar elemental abundances. The predicted fluxes differ by > 30%!

Borexino has recently set an upper limit on the CNO flux. SNO+ should do better because it is larger and has a lower $^{11}\text{C}$ background.
Solar $^8$B Neutrinos

Window from 2 – 5 MeV

Previously measured at low energies by Borexino and KamLand

$^{214}$Bi, $Q_\beta = 3.3$ MeV
- reject with $^{214}$Bi $\rightarrow ^{214}$Po $\rightarrow ^{210}$Pb coincidence

$^8$B neutrinos

$^{208}$Tl, $Q_\beta \sim 5$ MeV + $\gamma$s
- constrain by $^{212}$Bi $\rightarrow ^{212}$Po $\rightarrow ^{208}$Pb coincidence

Simulation includes:
- 99.8% $^{214}$Bi rejection
- $^{208}$Tl background constrained in the fit by a ±25% uncertainty

Note:
- less cosmogenic background in SNO+ than in KamLand
- Borexino 5 X smaller than SNO+

SNO+ can make a bin-by-bin comparison

Simulation:
780 tonne-year data

Scaled Borexino result
KamLAND observed antineutrinos from 53 reactors, average baseline 180 km, firmly established the MSW-LMA solution. SNO+ situated 240 km from one 6.3 GW station and 340 km from two ~ 3.3 GW stations. Expect about 90 events/year (oscillated).

The oscillation maximum from Bruce is pushed to higher energies than in KamLAND (constant L/E).

Distance to the other reactors is such that the second oscillation maximum appears. It so happens that the spectral features line up such that the peak in the spectrum is quite sensitive to $\Delta m^2$.

Sensitivity projections show that SNO+ can surpass the current KamLAND limits in about 3½ years of running.
Geo Neutrinos

SNO+ is located in the middle of ancient, thick, continental crust, an ideal location to help answer some of the open questions about Earth’s natural radioactivity:

• how much U and Th is in the crust?
• how much is in the mantle?
• is BSE model consistent with geo neutrino data?

Evidence for geo neutrinos first seen at KamLAND.

SNO+ should see a cleaner signal because of lower background from nuclear reactors:

• reactor/signal ~ 0.9 (SNO+), 4.4 for KamLAND

Spectrum shows that geo neutrinos are quite distinct from the reactor neutrinos, and that U and Th neutrinos can be separately identified.

SNO+ expects to detect about 54 events per year in the geo neutrino window; about 25 will come from reactor background.
Supernova Neutrinos

SN1987A
- observed by Kamiokande and IMB (water Čerenkov)
- provided important information about the mechanisms of supernova explosion

A liquid scintillator detector has a larger variety of reactions available – should provide even more information.

SNO+ could observe:

CC: \(\bar{\nu}_e + p \rightarrow n + e^+\) 260 events
\(^{12}\text{C}(\nu_e,e^-)^{12}\text{N}\) 30
\(^{12}\text{C}(\bar{\nu}_e,e^+)^{12}\text{B}\) 10

NC: \(^{12}\text{C}(\nu_x,\nu_x)^{12}\text{C}_{15.11}\) 60
\(\nu_x + p \rightarrow \nu_x + p\) 270

ES: \(\nu_x + e \rightarrow \nu_x + p\) 12

SNEWS: SNO+ will be a member

Type II SN at 10 kpc
Changes and Upgrades

Although re-using the SNO detector for a new experiment is a good idea, it does not come for free!

Many changes and upgrades are needed:

• the way in which the acrylic vessel is supported must be changed
• the vessel must be cleaned and free of radioactivity
• upgrades are needed for the electronics and DAQ
• new process systems are required
• different calibration sources and hardware are needed
• the vessel must be sealed to prevent the ingress of radon
• the liquid scintillator must be developed and procured
• Te must be purchased and purified
AV Support Ropes

In SNO the acrylic vessel filled with heavy water had to be held up.
In SNO the acrylic vessel filled with heavy water had to be held up.

In SNO+ the vessel filled with LAB has to be held down.

Up ropes were vectran, need to be replaced as well – 30 times too much potassium. All ropes will be fabricated from tensylon.

Hold down rope net overlays the vessel.

Umbrella keeps dust off the vessel and phototube sphere during construction.

Drilling holes for the anchor bolts.
Acrylic Vessel Sanding

Mine air - laden with radon.

$^{218}\text{Po}$ electrostatically attracted to AV.

$^{218}\text{Po}$ α-decay daughters implanted into the acrylic.

Long-lived $^{210}\text{Pb}$ - could be leached into the LAB.

The β-decay spectrum of $^{210}\text{Bi}$ is nearly degenerate with the CNO spectrum.

Studies at the end of SNO showed several times more Po α decays from above the water level than from below.

The inside of the AV has been exposed to mine air for several years – hence sand the inside.

About 2 μm will be removed.
More on sanding

However:

• readiness of sanding was stuck at 95%
• collaboration’s priority is double-beta decay and $^{210}$Pb background only a problem for CNO measurement
• some $^{210}$Pb will leach into water during water fill, though might be at a slow rate
• some could leach into LAB – purification system might remove it
• could be implanted so deeply into AV it won’t leach out
• can evaluate during $\beta\beta$ running, other mitigation strategies could be employed, if necessary

Thus don’t sand for now.
Acrylic Vessel Cleaning

Ladder Deployment in SNO+ Detector (Upper Hemisphere Cleaning)

Lower Hemisphere Cleaning
Electronics

Differences between SNO and SNO+

- much more light/MeV (400 hits vs. 9)
- lower threshold → higher event rate
  - 3.5 kBytes/s in SNO vs. 120 kBytes/s in SNO+
  - max sustained rate 300 kBytes/s vs. 2 MBytes/s
    - not enough bandwidth in SNO electronics
    - too much current for SNO trigger sum
- more isotropic distribution of light

Increase data bandwidth by putting local intelligence in each crate. Data are digitized and stored on ML403 board.

New card to sum triggers from all crates. Sums voltage rather than current. Digitized by CAEN digitizer.

Several other boards being refurbished.
The laserball was the workhorse for the optical calibration of SNO and was deployed monthly.

Because of the stringent radiopurity requirements and risk of contamination, we don’t want to deploy it as often in SNO+.

Therefore, it will be augmented by the Ellie system - (Tellie, Smellie, Amellie) – LED driven fibres mounted on the phototube sphere to monitor:

- PMT timing calibration and gain
- scattering and attenuation lengths

in real time with less risk of contamination.
Light will be emitted with varying:

- wavelength
- opening angle
- position
- direction

Each system is tuned to monitor a specific aspect of the detector response:

- **Tellie** – monitor timing ($T_0$ and time walk) and gain calibration of the PMTs.
- **Amellie** – measure light attenuation in detector volume using wide angle beams.
- **Smellie** – measure scattering within the detector volume using collimated beams at several wavelengths.
Other Calibration Sources

\(^{60}\)Co – 0.32 MeV \(\beta\), 2.5 MeV summed \(\gamma\)
- energy scale, multivertex reconstruction, pile-up

\(^{48}\)Sc – 0.66 MeV \(\beta\), 3.3 MeV summed \(\gamma\), close to Nd 0\(\nu\)\(\beta\)\(\beta\) end point
- energy scale, reconstruction, position dependence, Nd absorption

\(^{8}\)Li (Čerenkov source)
- only Čerenkov light in detector, no scintillation
- PMT efficiency, LAB absorption/re-emission timing

AmBe – n, 4.4 MeV \(\gamma\)
- Light yield, neutron propagation, reconstruction, Nd absorption

\(^{16}\)N – 6 MeV \(\gamma\)
- energy scale, sacrifice and contamination, check detector model in water fill
- alpha quenching, beta response, scintillator timing response

Radon source ball
- energy scale, reconstruction, position dependence

Low energy gamma source – to be determined
- energy scale, reconstruction, position dependence

Camera system – six cameras spaced around the phototube sphere
- locate sources within 1 cm (5 cm in SNO), monitor AV position

Extensive materials testing program – any material that can contact the LAB is tested for radon emanation and leaching of radioactive or other impurities
Calibration Source Deployment Hardware

- Side Rope Motor Boxes
- Deck Clean Room
- Umbilical Retrieval Mechanism
- Source Tube
- Gate Valve
- Glove Box
- Universal Interface
- Calibration Guide Tubes
- Side ropes
- Central rope
- Source Umbilical
- Rubbing Ring
- Phototube sphere
- Carriage & Weight
- Anchor Block
- Acrylic Vessel

Everything outlined in yellow needs to be changed.
SNO glove box and UI
- gaskets and single O-rings to seal against mine air
- a single cover gas system for D_2O and H_2O

Radioactivity requirements for SNO+ are much more stringent.

Mine air must not get in.

Leak rate goal is < 2 \times 10^{-6} \text{ mbar.L/s}
- seals are double O-ring or ConFlat
- UI is double O-ringed sealed to AV
- calibration sources will be kept either in deployment mechanism or storage box and will not be exposed to mine air
- separate cover gas systems
Oct 2012 – air fill – commission new electronics and DAQ
Ladder inside the acrylic vessel
Approximate Timeline

Oct 2012 – air fill – commission new electronics and DAQ
Nov 2012 – Apr 2013 - clean AV, install remaining new equipment
Universal Interface

Sits on top of acrylic vessel neck

- Ports for inserting calibration sources and for monitoring status of equipment inside acrylic vessel
- Glove ports for attaching ropes used to position calibration sources
- Pipes for introducing liquid into AV
- Ports for pumping space between double o-ring seals

Designed and fabricated at TRIUMF

Finished product will include motor boxes used to adjust rope tensions and lengths (currently being fabricated).
Approximate Timeline

Oct 2012 – air fill – commission new electronics and DAQ
Nov 2012 – Apr 2013 - clean AV, install remaining new equipment
May 2013 – Jul 2013 - water fill
Aug 2013 – Jan 2014 - water fill data
  • commission new hardware
  • check PMT mapping – some PMTs have been repaired/moved
  • re-establish optical model of the detector
  • get background estimates and channel efficiencies
  • develop energy/position reconstruction
  • tune data cleaning cuts
  • some physics – nucleon decay
Feb 2014 – Apr 2014 – scintillator fill
May 2014 - ? – run pure scintillator (a few months)
  • understand detector’s scintillator response
  • repeat most water fill activities
  • more physics - low energy solar data

When happy, start Te introduction and 0νββ-decay experiment
SNOLAB images

SNO cavity during excavation

outside SNOLAB entrance

inside SNOLAB
Mine gear

Outside the laboratory and inside
The original proposal was to re-use the SNO detector, filled with liquid scintillator, to make a measurement of pep neutrinos.

It was quickly realized that measurements of CNO, reactor, and geo neutrinos would come along for free. Hundreds of events will be observed in the event of a supernova in the Galaxy. And as well as all that, a double-beta decay experiment will be carried out.

A nice reincarnation of the detector that was originally used to unambiguously establish flavour change of electron neutrinos from the sun!
The SNO+ Collaboration

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$^{238}$U decay chain

Q-values for beta and alpha decays are given in MeV
Gamma energies are in keV
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Gamma energies are in keV