Reactor antineutrinos in SNO+

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The SNO+ experiment

Large-scale liquid scintillator (LS) experiment located 2 km underground at SNOLAB, Canada, it addresses a vast neutrino physics research programme [1].

Physics

- search for the Dirac or Majorana nature of neutrinos using the neutrino-less double beta decay ($0\nu\beta\beta$) of 130Te
- Δm^2_{21} extraction using reactor antineutrinos
- pep, CNO, and 8B solar neutrinos
- geo-neutrinos
- supernova neutrinos
- nucleon decay

Detector

With an overburden of ~6000 meter water equivalent it consists of:

> a 12 meter diameter spherical acrylic vessel (AV) which houses the detection medium

3 Phases

ultrapure water	1000 tonnes	9 months
organic LS (LAB+PPO)	780 tonnes	6 months
natural Te loaded LS	780 tonnes LS + 3 tonnes $^{nat.}$Te (1.3 tonnes ^{130}Te)	5 years

> ~9300 photomultiplier tubes (PMTs) pointed at the AV, and a small fraction directed outwards, providing ~55% coverage through the use of concentrators

> ~7000 tonnes of surrounding water (1700 tonnes between the PMTs and the AV and 5300 outside the frame supporting the PMTs)

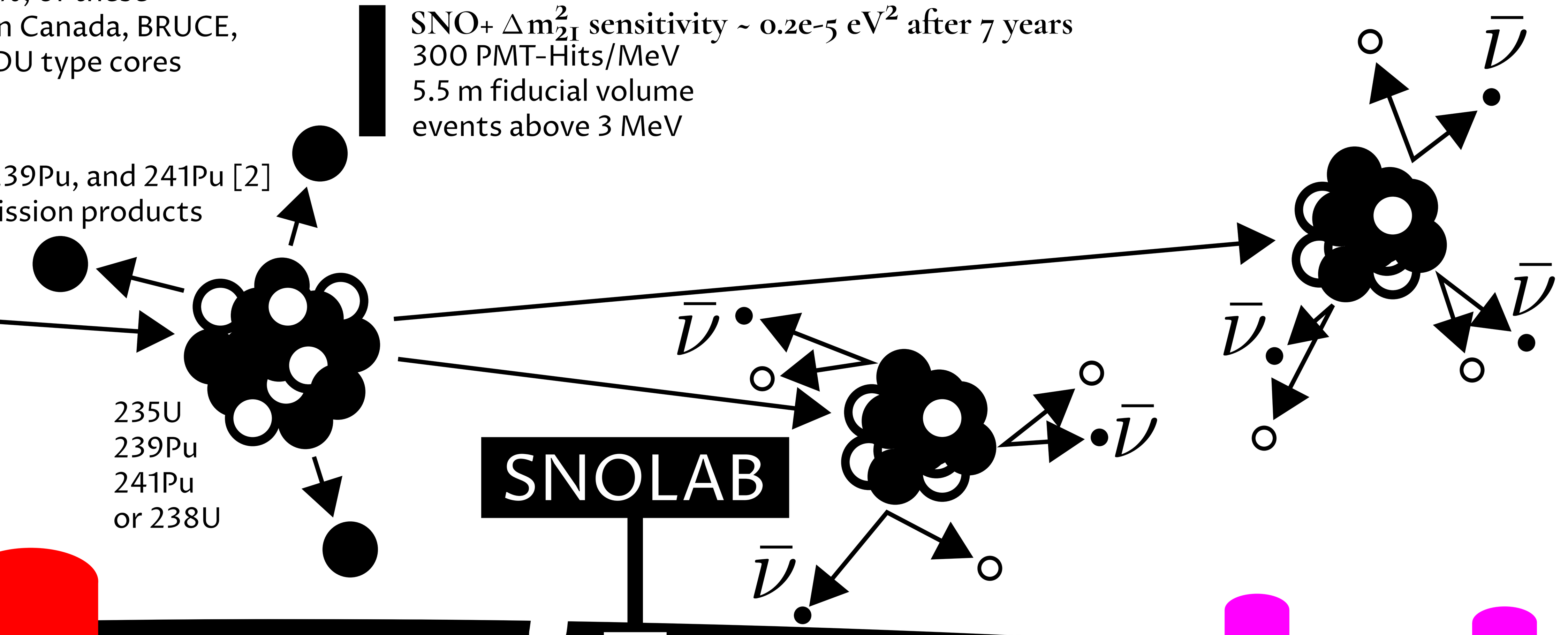
Reactor antineutrinos

Originating in the burning of nuclear fuel a significant fraction, ~60%, of these neutrinos that will hit the detector, come from three power plants in Canada, BRUCE, DARLINGTON, and PICKERING (Figure 1). These reactors have CANDU type cores featuring constant refuelling.

Nuclear fission

99.9% of the energy in a reactor is from fission of 235U, 238U, 239Pu, and 241Pu [2]

~6 electron antineutrinos are emitted from beta decays of the fission products



3000 MW reactor

1.9×10^{22} MeV released per second

5.5×10^{20} antineutrinos released isotropically per second

250 km away from the reactor 7.2×10^{4} antineutrinos cm^{-2} s^{-1}

Neutrino oscillations

Propagating away from a nuclear reactor the initial neutrino pure flavor state $|\nu_e\rangle = \sum U_{ej}|\nu_j\rangle, j = 1,2,3$, will undergo changes of the component mixed mass states phases as a function of the distance travelled and the carried energy leading to deformations of the energy spectrum when detecting neutrinos of the initial flavor as shown in Figure 1.

Survival probability

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L, E_{\bar{\nu}_e}) = \cos^4\theta_{13}\left(1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}\cdot L}{4E_{\bar{\nu}_e}}\right)\right) + \sin^4\theta_{13}$$

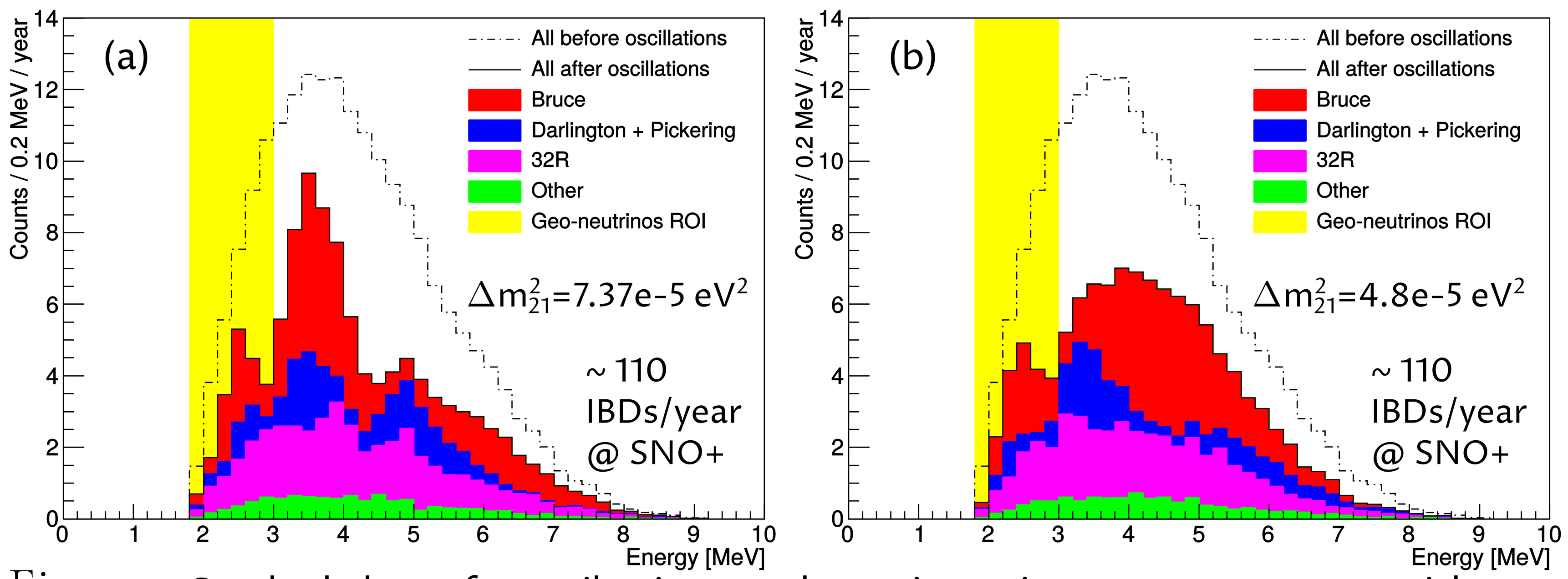


Figure 1 Stacked plots of contributions to the antineutrino energy spectrum with fluxes from all commercial nuclear reactors in the world (~ 450 reactor cores) based on a Monte Carlo simulation of the inverse beta decay (IBD) interaction in SNO+. For (a) the 2016 global fit oscillation parameters from PDG [3] are used while in (b) the value of Δm^2_{21} was replaced with the Super-Kamiokande result [4].

SNO+ Δm^2_{21} sensitivity ~ 0.2e-5 eV^2 after 7 years

300 PMT-Hits/MeV

5.5 m fiducial volume

events above 3 MeV

Detection I: neutrino interaction

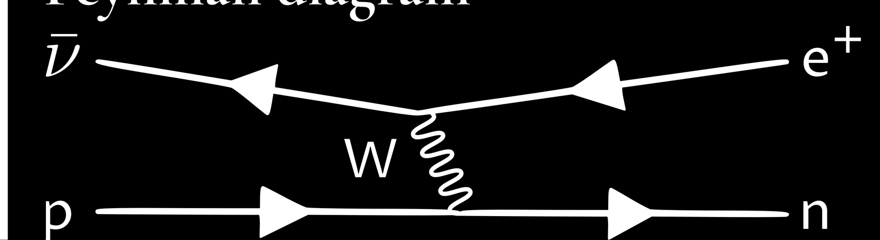
Reactor antineutrinos have low energies, up to 10 MeV, and are detected in SNO+ via charge current interactions with the protons in the liquid scintillator.

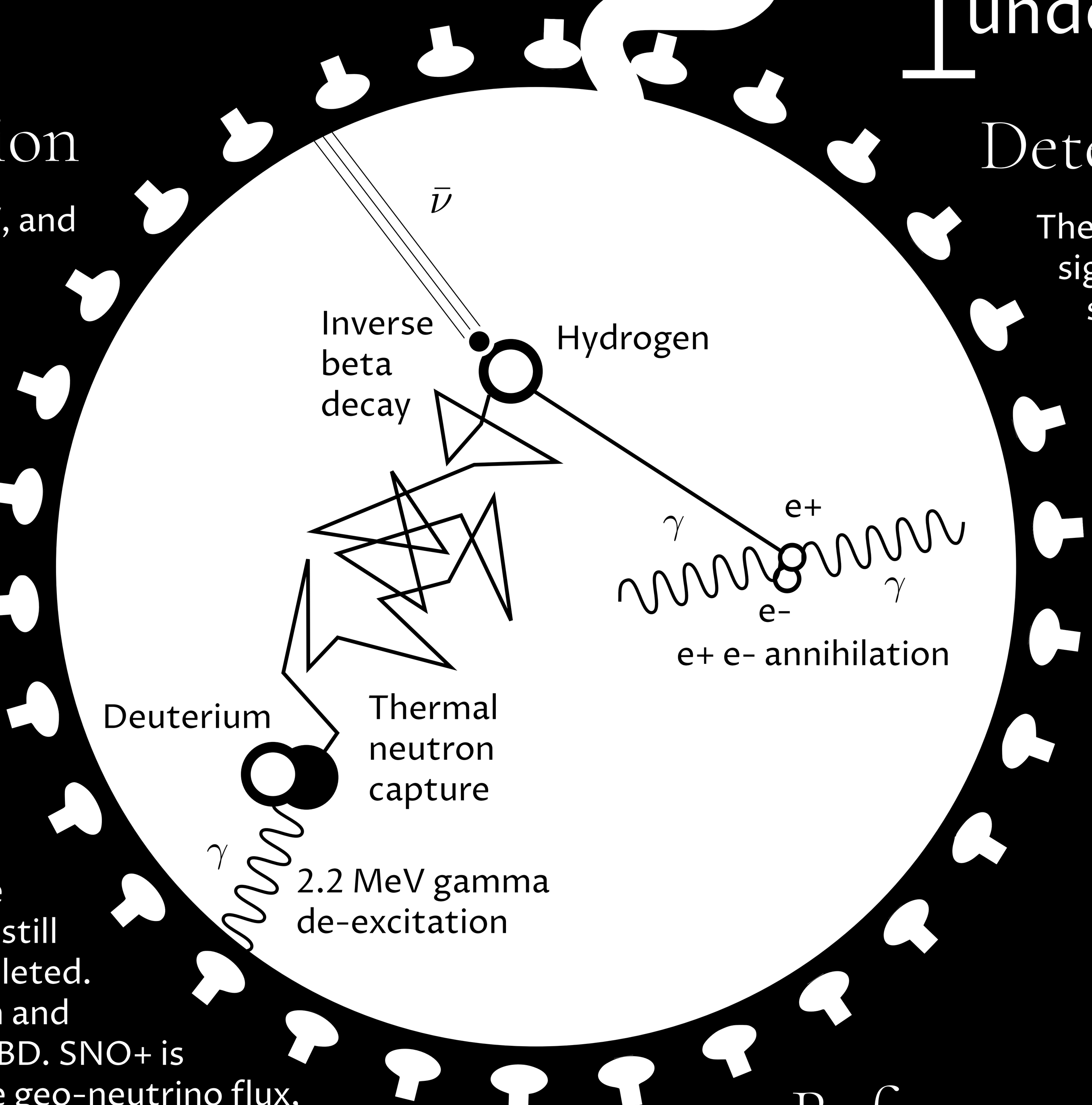
Inverse beta decay (IBD)

$\bar{\nu} + p \rightarrow e^+ + n$

IBD$_{threshold}$ = 1.8 MeV

Feynman diagram



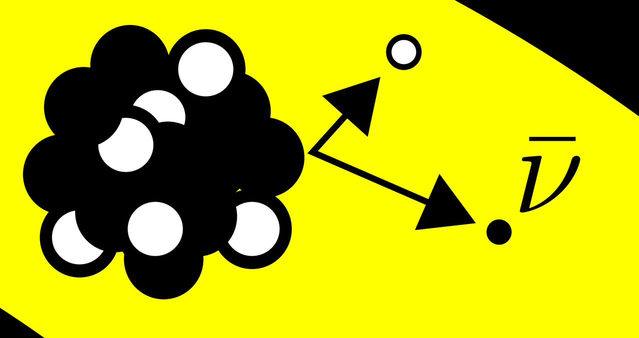


Geo-neutrinos

From inside Earth, the dacays of the naturally occuring radioactive elements 238U, 232Th, and 40K constitute the main sources for these neutrinos. These nuclei are still present in Earth's crust and mantle, the core being depleted. From these, only the decay products from the Uranium and Thorium isotopes have enough energy to interact via IBD. SNO+ is expected to measure a higher crust contribution to the geo-neutrino flux, in comparison with data from experiments at other locations, due to local geology [5].

Earth's crust and mantle up to 2900 km deep

Earth's core



Detection II: delayed coincidence

The final state particles in the IBD process give a definite signature in the detector, the associated events are separated by ~200 μs and ~30 cm inside the detector.

Signals

prompt ~ns: the positron quickly losses energy while ionizing the scintillator medium until annihilating with an electron

delayed ~μs: the neutron thermalizes and is usually captured on Hydrogen which then transitions to ground state by releasing a 2.2 MeV gamma ray

Antineutrino energy

$E = E_{prompt} + (M_n - M_p) - m_e$

$= E_{prompt} + 0.8$ MeV

Backgrounds

true coincidences: by alpha particles from 210Po leached from the AV

α + 13C -> 16O + n

fake coincidences: neutrons from external background sources in coincidence with other signals inside the detector

References

[1] S. Andringa et al. (SNO+ collaboration), Adv. High Energy Phys. 2016, 6194250 (2016).
[2] A. C. Hayes and P. Vogel, Ann. Rev. Nucl. Part. Sci. 66, 219-244 (2016).
[3] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).
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Acknowledgements

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