Detecting Neutron Bursts with the HALO Supernova Neutrino Detector

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$$CC: \quad \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV}$$
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV}$$
$$NC: \quad \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV}$$
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}$$

Figure 1: Charged and Neutral Current neutrino reactions for a lead-based detector.

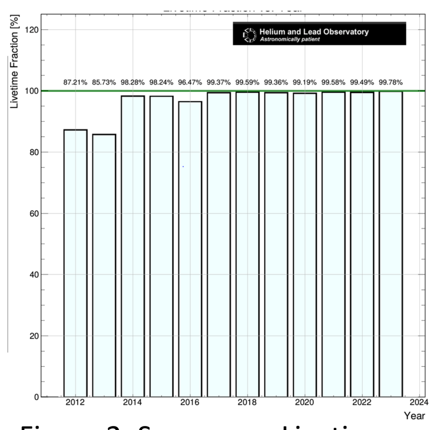


Figure 2: Supernova Livetime Fraction: May 2012 to Current.

ABSTRACT

HALO, the Helium and Lead Observatory, has been operating at SNOLAB for eleven years as a low-maintenance, high-livetime supernova neutrino detector. Since October 2015 HALO has been providing low threshold and very low latency supernova alarms to the SuperNova Early Warning System (SNEWS) coincidence servers. The HALO detector is principally composed 79 tonnes of lead, from a decommissioned cosmic ray station, and is instrumented by 368 m of SNO's ultra-low activity He-3 neutron counters. Supernova neutrinos interacting with the lead target may produce one or two neutron emission through CC or NC excitation of the lead nuclei. HALO detects these neutrons with an average efficiency of 28% and an extended burst of detected neutrons would be consistent with a galactic supernova explosion. The background detected neutron rate in HALO, from various sources, is 15 mHz. Two prompt sources of neutron bursts are muon spallation events (the low cosmic ray muon rate in SNOLAB results in close to two muons per day traversing HALO), and spontaneous fission of U-238 built into HALO. With a neutron thermalization and capture time of 200 usec these prompt bursts are not confused with supernova candidate events. As a large, low-background, and long-running lead-based neutron detector there is an interest in exotic prompt signatures that HALO might have sensitivity to. The collaboration will present its first, preliminary, neutron multiplicity distribution from a reasonably large dataset.

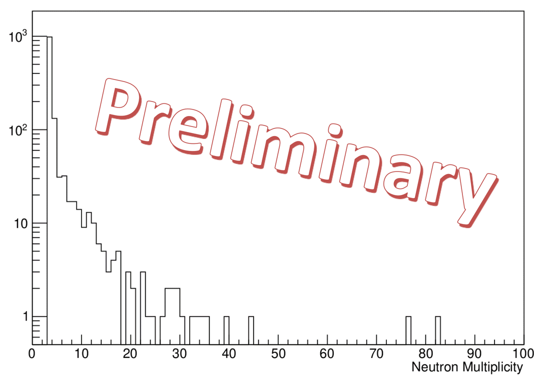


Figure 13: Preliminary neutron burst multiplicity spectrum from 5.6 years of HALO livetime. This dataset contains 192 bursts with 5 or more events.

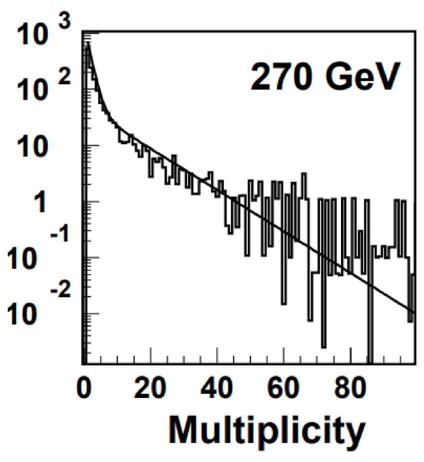


Figure 14: Simulated neutron multiplicity spectrum for muons on liquid scintillator from Wang. et. al. arxiv:hep-ex/0101049. Average muon energy is 350 GeV.

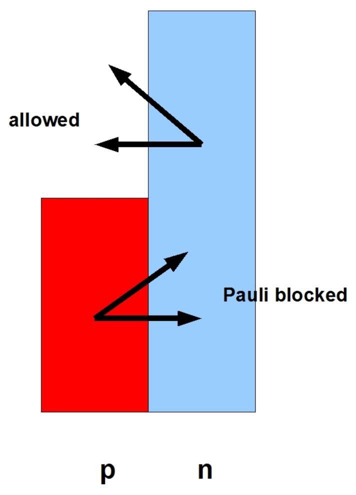


Figure 3: Pauli blocking of p → n transitions renders lead-based detectors insensitive to $\bar{\nu}_e$ CC reactions. The high Z of lead provides significant Coulomb enhancement to the ν_e CC cross-section.

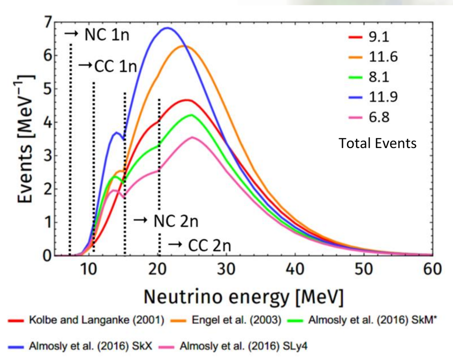


Figure 4: Expected neutrino interaction spectrum for the LS220-z9.6co model at 10kpc from a variety of cross-section models: A. Gallo Rosso arxiv:2012.12579
Note that the interaction energy is unresolved in HALO.

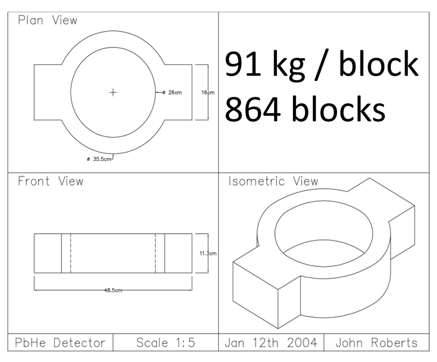


Figure 5: The lead for HALO was obtained from a decommissioned cosmic ray station in Deep River, Ontario and re-used in its original form.

HALO - a Helium and Lead Observatory

A "SN detector of opportunity" / An evolution of LAND – the Lead Astronomical Neutrino Detector, C.K. Hargrove et al., Astropart. Phys. 5 183, 1996.

"Helium" – because of the availability of the ^{3}He neutron detectors from the final phase of SNO
+
"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors

HALO Objectives and Philosophy

- to provide ν_e (dominantly) and ν_x sensitivity to the SN detection community now
- to provide a long-term, high live-time dedicated supernova detector to explore the feasibility of scaling a lead-based detector to kT mass
- Achieve these objectives by keeping HALO
  - Very low cost
  - Low maintenance
  - Low impact in terms of lab resources

Pb Nuclear Physics

- High Z increases ν_e CC cross-sections relative to $\bar{\nu}_e$ CC and NC due to Coulomb enhancement.
- CC and NC cross-sections are the largest of any reasonable material though thresholds are high
- Neutron excess (N > Z) Pauli blocks
  $\bar{\nu}_e + p \rightarrow e^+ + n$
  further suppressing the $\bar{\nu}_e$ CC channel
- Results in flavour sensitivity complimentary to water Cerenkov and liquid scintillator detectors

Other Advantages
- High Coulomb barrier → no (α, n)
- Low neutron absorption cross-section (one of the lowest in the table of the isotopes) → a good medium for moderating neutrons down to epithermal energies

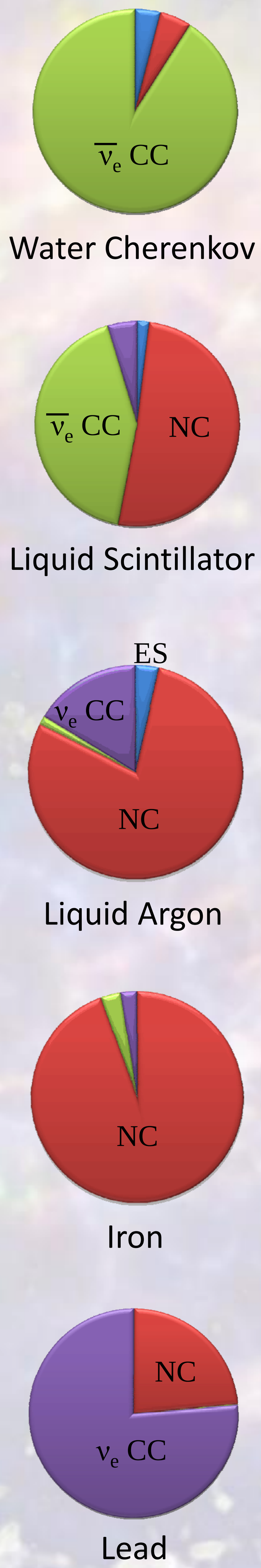


Figure 8: Flavour sensitivity of detector response as a function of the SN neutrino detection technology. Note that these diagrams need assumed small θ_{13} and that the Argon one in particular needs to be updated in this respect. Note also that low detector thresholds have been assumed and that these may also not be obtainable by particular detectors. Raising hardware detector thresholds will alter the distributions. Detailed flavour distributions are also sensitive to neutrino temperatures and in the case of lead a hard energy distribution has been assumed following the work of Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003).

HALO Backgrounds

- Gamma and Beta events are well-separated from neutrons by integrated charge.
- Bulk α contamination in the CVD nickel tubes gives a negligible 22 +/- 1 events in neutron window per day for the whole array
- Fast and thermal neutrons in SNOLAB occur at 4000 and 4100 neutrons/m^2/day respectively
- (α, n) reactions not simulated in the HALO GEANT MC but the threshold in Pb is 15.2 MeV
- With water shielding the neutron background rate is 15mHz (1 per minute)

Neutron Bursts

- Supernova neutrinos will appear as a burst of neutrons 20 ms to 10 seconds long.
- 0.2 ms neutron thermalization + capture time provides decent timing resolution
- Other sources produce prompt bursts of neutrons:
  - Fission
  - Muon Spallation
    - 2 muons/day at 6000 meters water equivalent depth
  - Exotic Processes
- Supernova trigger sent to SNEWS if:
  - 4+ neutrons in 10 ms to 2 seconds
  - Position and integrated charge of events is consistent with supernova neutrinos
- Rate of random coincidences passing the SNEWS trigger is much less than 1 per year.

Preliminary Burst Multiplicity Analysis

- Run Selection:
  - All shielding installed
  - 24 hour runs
  - Timing calibrations working properly
  - All channels working properly
  - 2054 days (5.6 years) of 4060 days passed cuts
- Event Selection:
  - Integrated charge > 250 ADC counts for each event
    - 99% acceptance for neutrons
  - 3+ events within 3 ms window
  - ADC spectrum consistent with neutrons
    - Removes electronic noise
    - Minimizes Beta / Gamma leakage
    - 85% acceptance
- No current correction for position-dependent capture efficiency

Summary

- HALO is complete and continuous operation of the full detector began on May 8th 2012 providing sensitivity to the ν_e and ν_x components of a supernova
- HALO is now a full participant in SNEWS

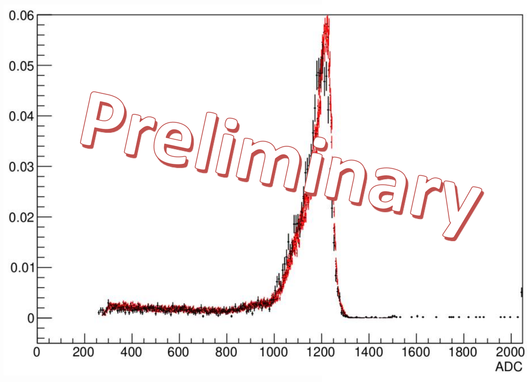


Figure 15: Integrated charge for neutron calibrations (red) and events from all burst candidates (black).

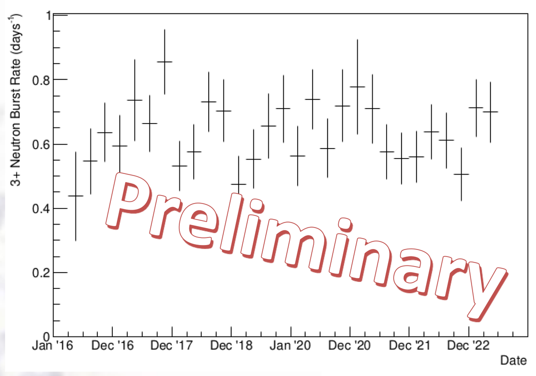


Figure 16: Rate of burst candidates vs calendar date

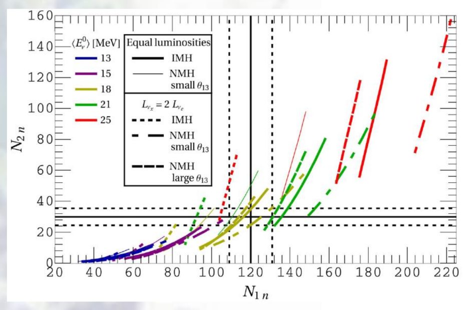
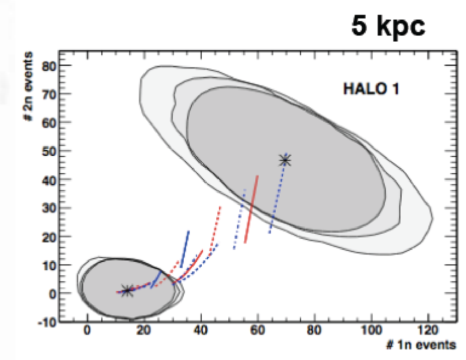


Figure 17: Distinct 1n and 2n emission thresholds in lead provide the possibility to measure neutrino temperatures and pinching parameters. N_{1n} and N_{2n} per kT from Väänänen and Volpe, arXiv:1105.6225.



ε = 40%,50%,60%

Figure 18: Ability of HALO to measure neutrino temperature and pinching parameters for a 5 kpc SN as a function of overall n efficiency. March 2012 APS, K. Scholberg.

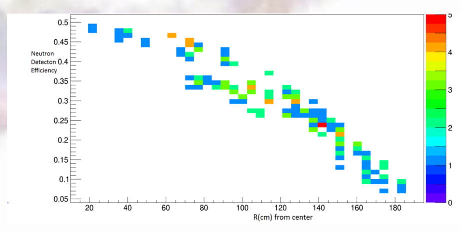


Figure 11: Neutron Detection Efficiency vs calibration source radius. 2017, C. Bruulsema

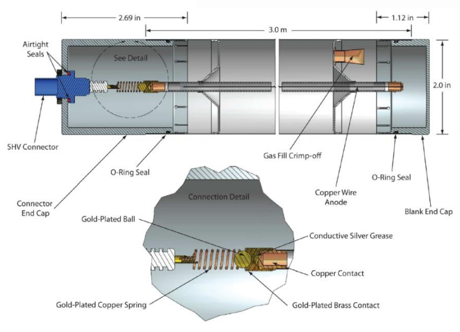


Figure 6: The neutron detectors for HALO are the ^{3}He detectors from the 3rd phase of SNO. For use in HALO they were re-fitted with new endcaps.

Figure 7: The front face of one of 32 three-meter-deep columns of lead blocks showing four ^{3}He counters mounted in a moderator assembly.

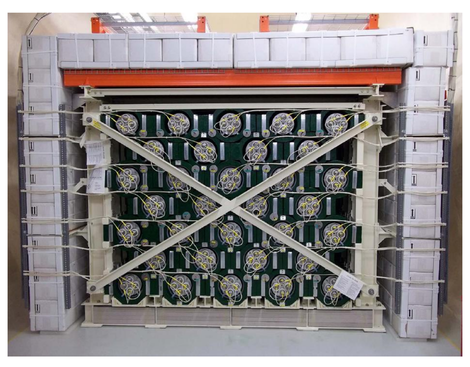


Figure 9: The assembled HALO detector, complete with the exception of the front shielding wall. Continuous readout of the full detector began May 8th 2012.

$n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p + 764\ \mathrm{keV}$

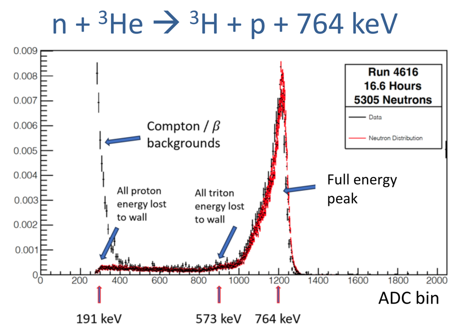


Figure 10: Integrated charge for neutron detections (red) and a sample run (black).

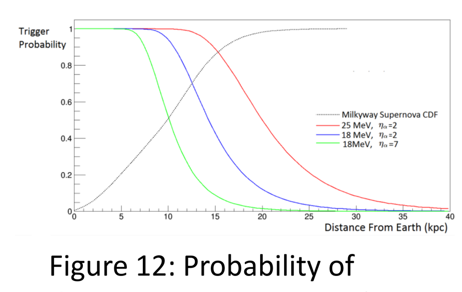


Figure 12: Probability of detecting 4 neutrons within 2 seconds for various pinched fermi-dirac neutrino spectra. At 15 kpc, the probabilities are 9%, 43%, and 89%.
C. Bruulsema, 2017

HALO joined the Supernova Early Warning System, SNEWS, in October 2015.

HALO Collaborating Institutes:

Georgia Southern University, Laurentian University / Université Laurentienne, University of Washington, SNOLAB, The University of North Carolina at Chapel Hill, DigiPen Institute of Technology, Duke University, Technische Universität Dresden, Pacific Northwest National Laboratory, ICRR Institute for Cosmic Ray Research University of Tokyo, UMD Duluth, TRIUMF

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