Calibration of HALO
(Helium And Lead Observatory)
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June 15, 2016
Supernovae

- When the inert iron core of a star reaches 1.4 solar masses, it collapses
- 99% of the released energy is in the form of neutrinos

http://www.space.com/17075-pictures-chandra-x-ray-observatory-space-telescope.html
https://www.spacetelescope.org/images/
HALO consists of an array of helium-3 counters in 79 tons of lead shielded by water and plastic.
Neutrino Detection

$\nu_e + Pb \rightarrow e + Bi^* \
Bi^* \rightarrow Bi + \gamma + n$

$n + ^3 He \rightarrow T + p + 764 KeV$
HALO is ready to provide unique flavor sensitivity

- 95% duty factor since September 2012
- Connected to SNEWS since October 9 2015
- Interruptions will get shorter once shutdown and start-up of halo is automated.

- HALO is the only lead-based supernova detector, giving unique electron neutrino sensitivity.
- Energy resolution from single vs double neuron events
Calibration with a Cf252 source has advantages caused by the multiplicity distribution

- Fixed high multiplicity: Multiplicity counting error drops by a factor of $\sqrt{1-E}$, single counting error increases.
- Cf multiplicity: 0 to 8 neutrons, $3.75718 \pm 1.27$ neutrons per fission
  → known number of fissions still gives better information than a perfectly known source strength

\[
\delta E = \sqrt{\sum_{k=0}^{8} k^2 \sum_{j=k}^{8} \left( \frac{1}{k} \right) E^k (1-E)^{j-k} p(j) / \sqrt{n_f*3.75718}}
\]

\[
\delta E = \sqrt{\frac{E}{n_f*3.75718}}
\]

**Fit and count neutron capture efficiency errors**
A fit function based on the likelihood of detecting different multiplicities models the detected distribution well

- First order fission pileup:

\[ N_i = n_f \sum_{j=0}^{16} \binom{j}{i} E^i (1 - E)^{j-i} \times \left( (2 \times \exp\left(-\frac{n_f \times W}{T}\right) - 1) \times p(j) + (1 - \exp\left(-\frac{n_f \times W}{T}\right)) \times pp(j) \right) \]

- Counter dead time gives a lower efficiency \( E' \) after the first neutron:

\[ N_i = n_f \sum_{j=0}^{16} \sum_{k=0}^{j-i} \binom{j-k-1}{i-1} E E'^{i-1} (1 - E')^k \times (1 - E')^{j-k-1} \times \left( (2 \times \exp\left(-\frac{n_f \times W}{T}\right) - 1) \times p(j) + (1 - \exp\left(-\frac{n_f \times W}{T}\right)) \times pp(j) \right) \]

- Multiplicity analysis can determine both source activity and neutron capture efficiency
Different procedures still have some unknown but manageable inconsistencies

Closed Detector: 192 points, 40 hours of data

- Fission rate of 22.8338 ± 0.0210 Hz March 9, Verified by AmBe neutron source comparison of 22.9±0.3 Hz
- Chi-squared 1227.5/1140: p=0.0358

Open Detector: 125 points, 8 hours of data

- Different fission rate of 22.475 ± 0.0354 Hz!
- Currently seems fission rate is lower with low efficiency and low data per efficiency fit.
Preliminary comparisons between the calibration data and current montecarlo are close

Closed Detector: 6 points compared
- Chi squared 20/6, relative error 1.5%

Open Detector: 17 points simulated for efficiency
- Chi squared 18/17, relative error 3.5%

Neutron detection efficiency for neutrons from lead is about 30%.
HALO can effectively discriminate against non-supernova bursts

Half of supernova neutrinos arrive within the first two seconds.

- Trigger threshold: now 4 neutrons in two seconds (was 6 without front shielding)
- Muon induced spallations create burst of neutrons about once per week, but these are filtered by their short duration
- Electronic noise, gamma, and alpha counts excluded by neutron capture ROI and counter wall effects

[Image: Spallation Event]

[Graph: Energy Spectrum with red and blue lines, indicating background data x5 and source data, with axes for Deposited Energy and Counts]
HALO can detect supernovae throughout most of the Milky Way

Resulting range: 18 kpc

- Expected SNEWS alarm rate of 2.36 per year (alarm rate required to be less than 6/yr)
- 3 alarms sent from open detector (1.15 expected)
The HALO Collaboration

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Funded by:
halo.snolab.ca
Backup Slides
Cf252 multiplicity fit

Pile-up multiplicity (first order)

\[ N_i = n_f \sum_{j=0}^{16} \binom{j}{i} E^i (1 - E)^{j-i} \times \left( (2 \times \exp\left( -\frac{n_f \times W}{T} \right) - 1 \right) \times p(j) + \left( 1 - \exp\left( -\frac{n_f \times W}{T} \right) \right) \times pp(j) \]

Busy Channels → E'<E

\[ N_i = n_f \sum_{j=0}^{16} \sum_{k=0}^{ji} \binom{j-k-1}{i-1} E^k E'^{i-1} (1 - E)^{j-k-1} \times \left( (2 \times \exp\left( -\frac{n_f \times W}{T} \right) - 1 \right) \times p(j) + \left( 1 - \exp\left( -\frac{n_f \times W}{T} \right) \right) \times pp(j) \]

E' Calculations

\[ L_r = \sum_i p_i^2 \]
\[ L_t = \frac{k}{k + (n-k)(1-L_r)} \]
\[ \delta L_r = 2 \times \sqrt{\sum_i a_i^4} \]
\[ \delta(1 - L_t L_r) = \frac{\sqrt{L_r^2 (1 - L_r)^2 nk(n-k) + n^2 k^2 (\delta L_r)^2}}{(k + (n-k)(1-L_r))^2} \]

Counting errors

\[ dE = \frac{\sqrt{\sum_{k=0}^{8} k^2 \sum_{j=k}^{8} \binom{j}{k} E^k (1 - E)^{j-k} p(j)}}{\sqrt{n_f \times 3.75718}} \]
Cf252 multiplicity fit

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</table>

Cf252 multiplicity fit

Neutron Multiplicity, Source at Tube 33-10 Z=0 for 2 hours

Counts

Counts

Neutron Multiplicity, Source at Tube 61-11 Z=120cm for 111 minutes

Entries 127928
Mean 2.519
RMS 1.02
χ² / ndf 32.02 / 9
Prob 0.0001975
norm 1.57e+05 ± 4.69e+02
e 0.4645 ± 0.0010
E/E 0.9619 ± 0.0002

Entries 70633
Mean 1.823
RMS 0.5812
χ² / ndf 0.9325 / 5
Prob 0.9678
norm 1.444e+05 ± 8.739e+02
e 0.176 ± 0.001
E/E 0.9594 ± 0.0004