Calibration system for PROSPECT-II

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On behalf of the
PROSPECT Collaboration

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

B13.00001: The Design and Expanded Physics Reach of the PROSPECT-II Detector Upgrade
B13.00003: Joint Isotope-Dependent Analysis of the Daya Bay and PROSPECT Reactor Antineutrino Spectra
B13.00004: A Joint Analysis of the PROSPECT and STEREO ^{235}U Antineutrino Spectra

E18.00004: Optical Photon Tracking in GEANT-4 for the PROSPECT-II Detector Upgrade
E18.00005: Calibration system for PROSPECT-II
E18.00006: Machine Learning Analysis of PROSPECT Data

Y18.00006: PROSPECT's latest results
Y18.00007: Improving PROSPECT Neutrino Measurements with Single Ended Event Reconstruction

X10.00007: Cosmic ray boosted dark matter at PROSPECT—theory and propagation
X10.00008: Cosmic ray Boosted Dark Matter at PROSPECT – Experimental Analysis

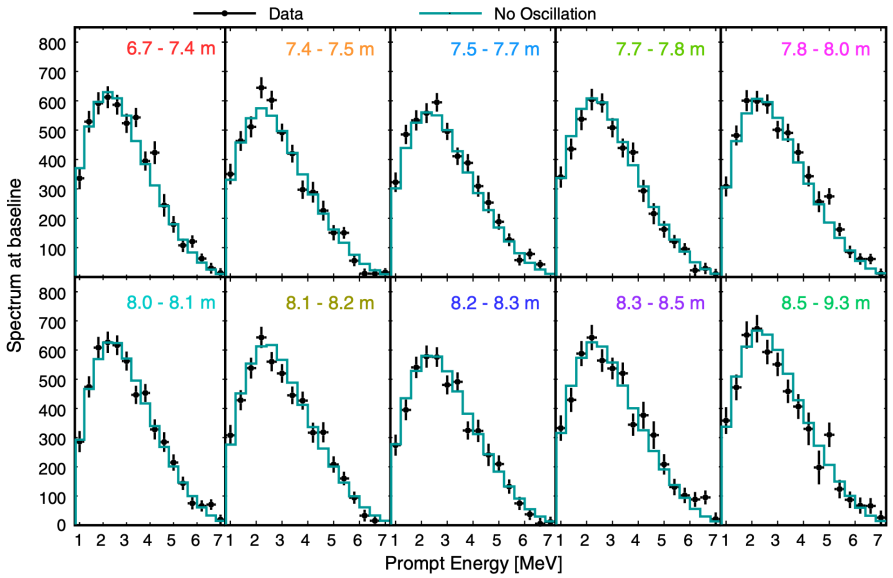
Outline

- PROSPECT-I physics results
- PROSPECT-I calibration
- Changes in PROSPECT-II upgrades
- Results of R&D study on P-II calibration
- Summary

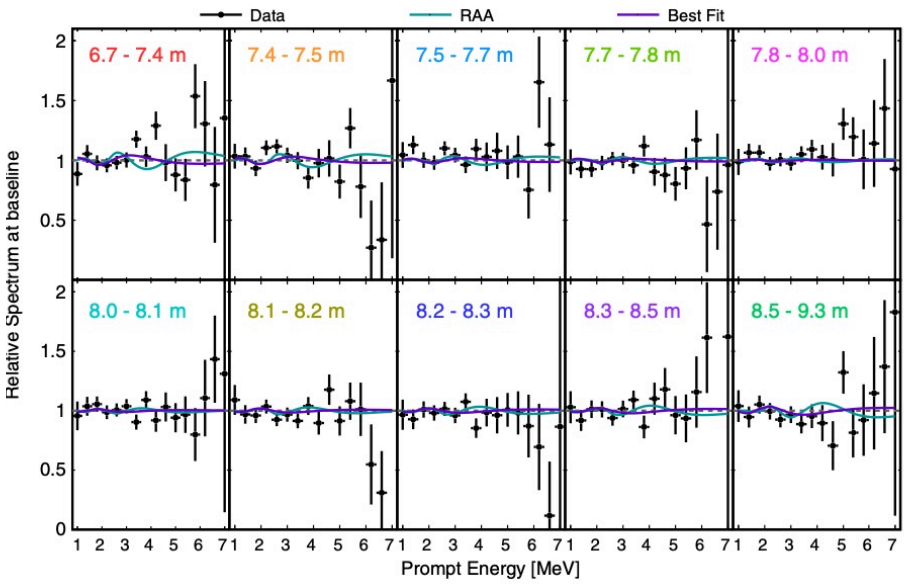
PROSPECT spectrum

- Per-baseline IBD spectra offers model-independent search for sterile neutrino oscillation

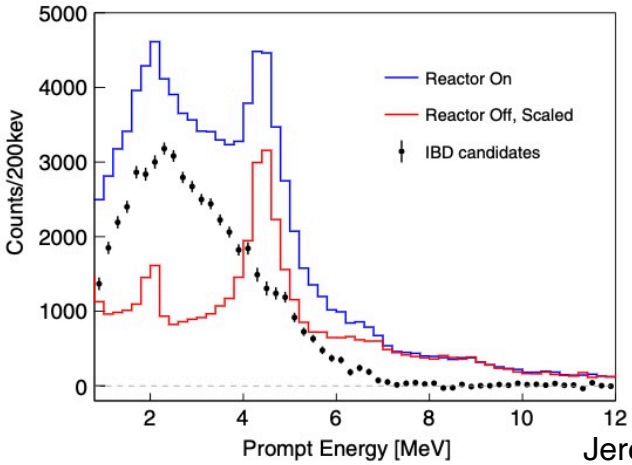
Absolute spectra



Relative spectra



- High statistics(~50k) IBD candidates energy spectrum from ^{235}U core



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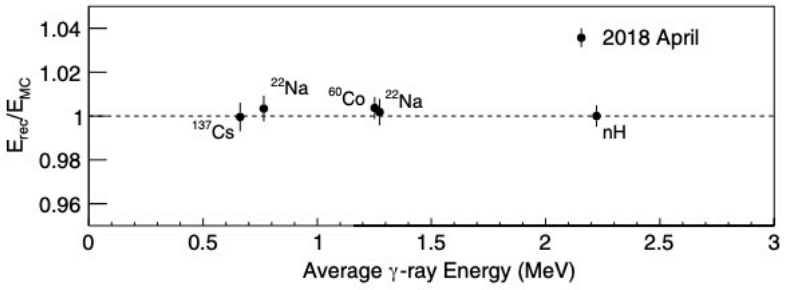
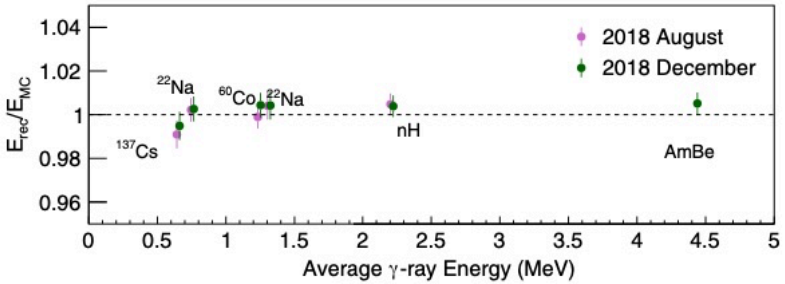
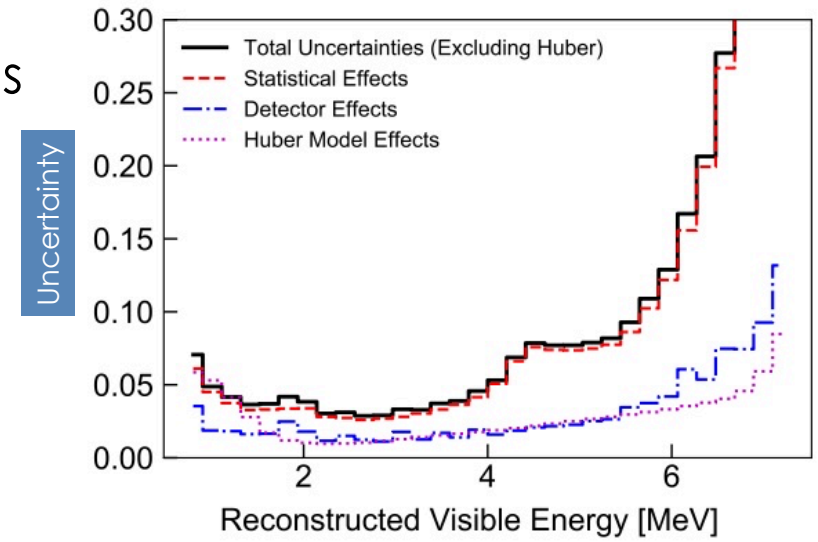
PROSPECT energy scale calibration

- Energy scale calibration ensures the energy reconstruction within +/-1% uncertainty and consistent across the data-taking period





- PROSPECT IBD candidate spectrum is currently still statistics-dominated



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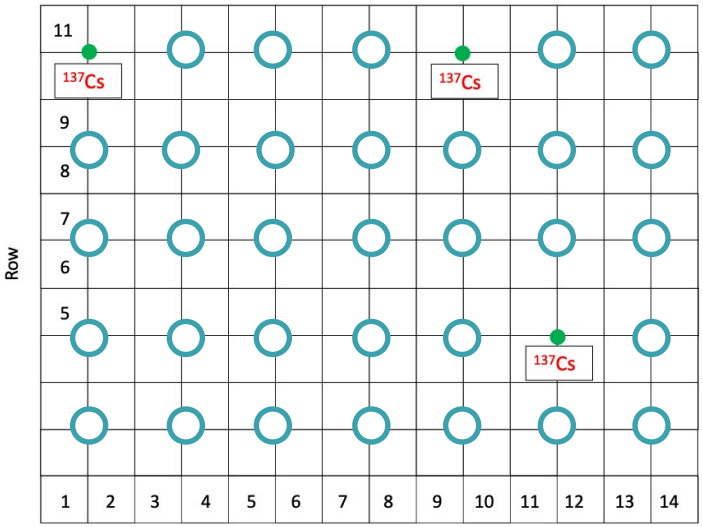
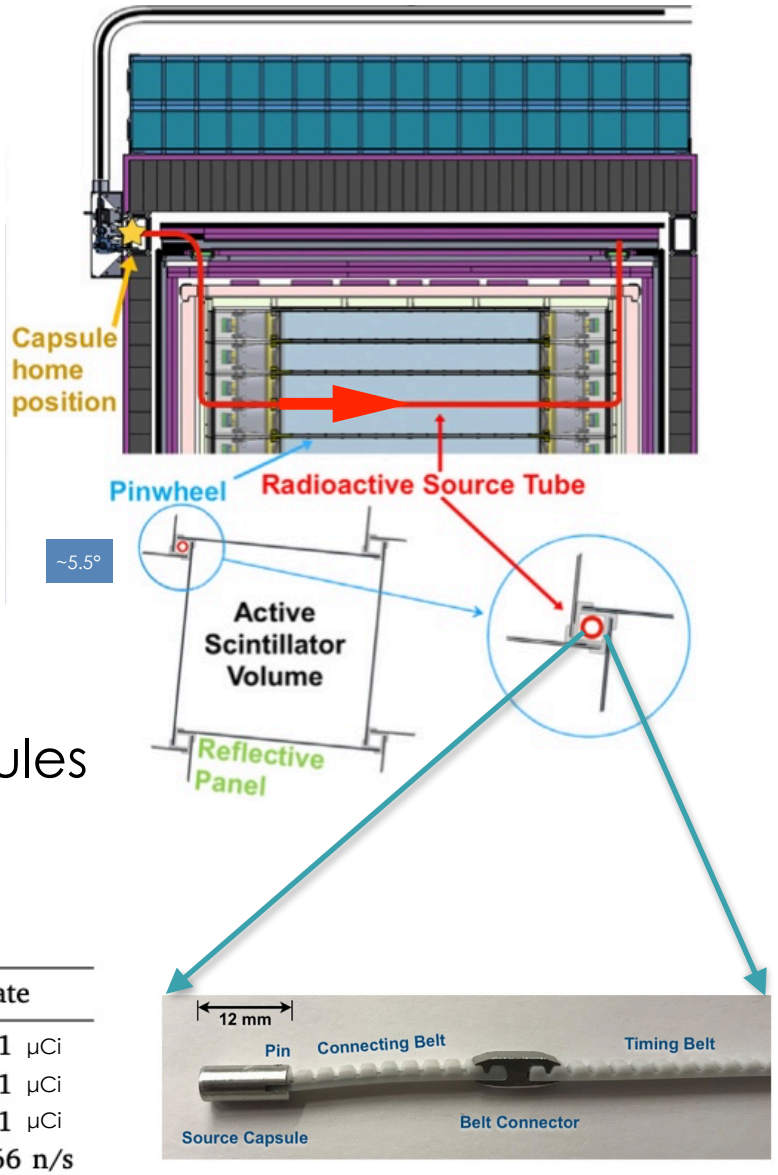
P-I Calibration system





- 14x11 segments and 5x7 source tubes
- ~5° tilted pinwheels house source capsules transported by stepper motor

Table 1
Calibration sources and their uses.

Source	Type	γ Energy (MeV)	Primary purpose	Rate
^{137}Cs	Gamma	0.662	Segment comparison	0.1 μCi
^{22}Na	Gamma	2×0.511, 1.275	Positron, edge effects	0.1 μCi
^{60}Co	Gamma	1.173, 1.332	Energy scale	0.1 μCi
^{252}Cf	Neutron	2.223 (n-H capture)	Neutron response	866 n/s
AmBe	Neutron	–	Neutron response	70 n/s

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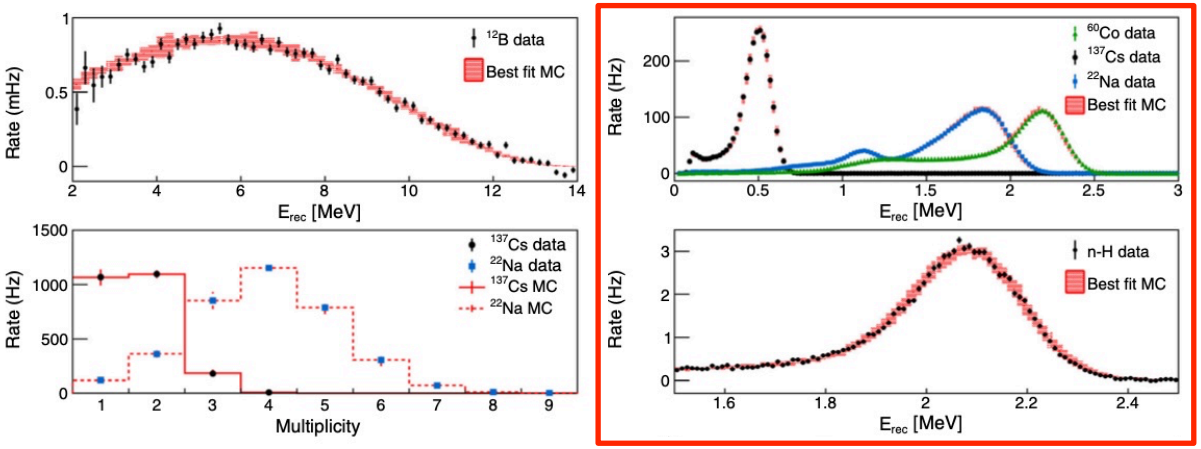
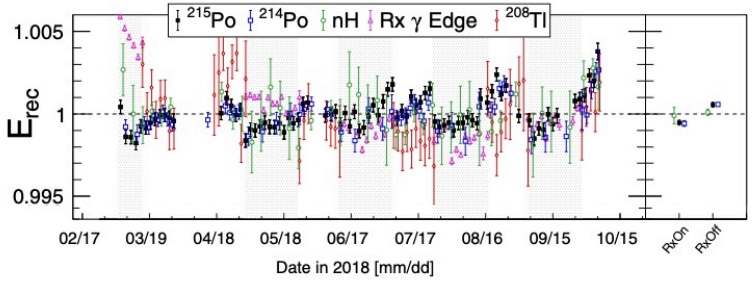
P-I Calibration result

- Internal radioactive sources + cosmogenic ^{12}B events for energy calibration
- Detector non-linearity model is best fitted to data in both spectrum and event multiplicity

Internal sources



- Achieved sub-percent level stability in energy reconstruction for various types of events



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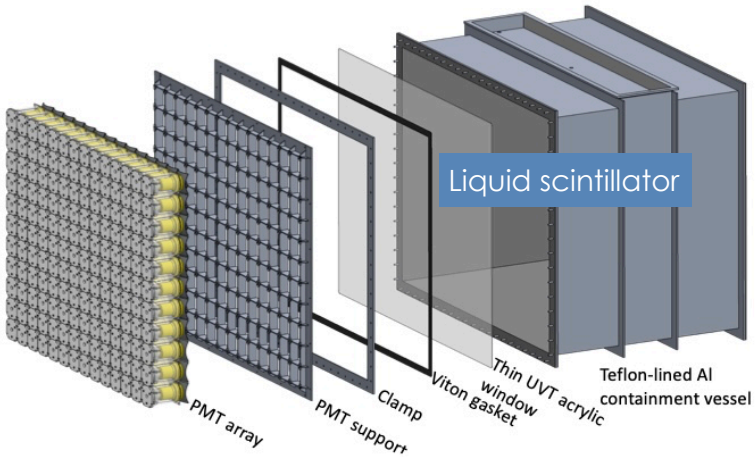
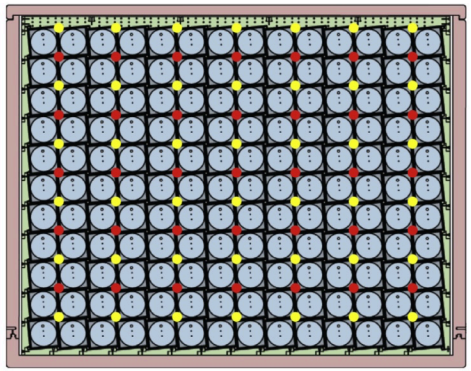
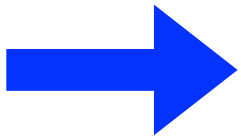
Preliminary detector design for PROSPECT-II

- Several PROSPECT PMTs showed current instability
- Separate PMTs from liquid scintillator volume to improve long term stability
- Simple and rigid to be redeployed at other reactor sites
- External calibration source

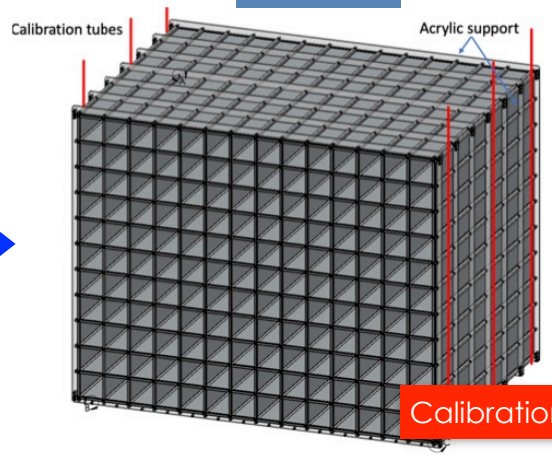


P-I design





P-II design



Calibration tubes

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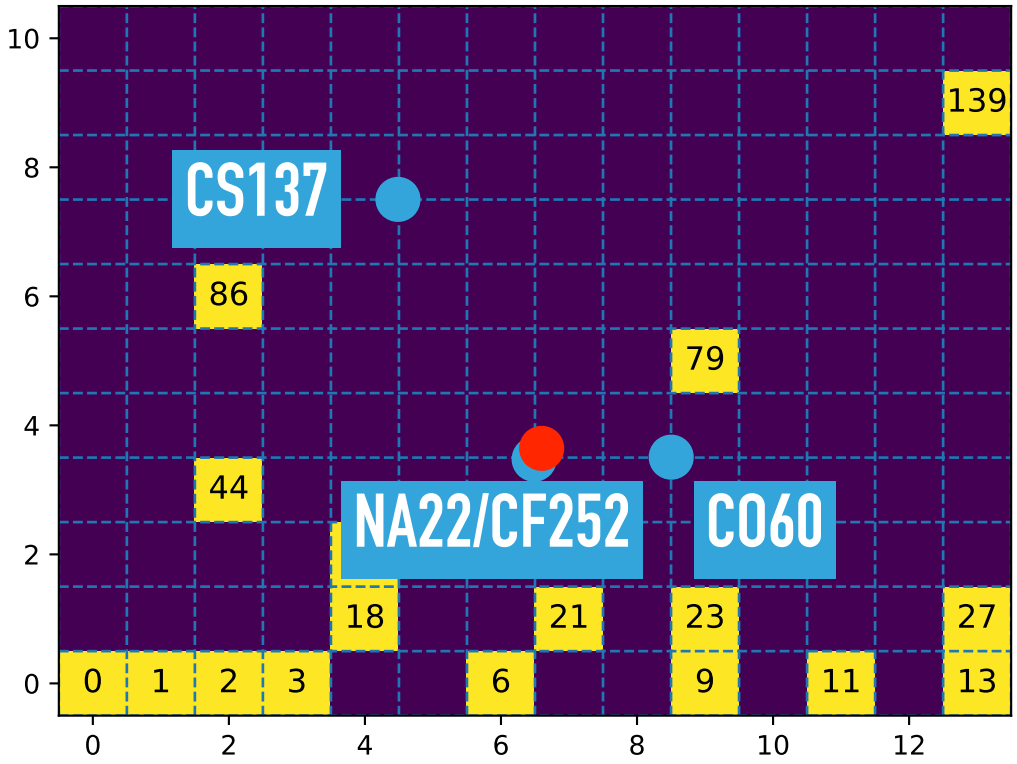
External calibration performance simulation

- Can external calibration perform as well as we had in PROSPECT?
- What level of degradation should we expect?
- Any extra internal modification in PROSPECT-II needed?

Internal calibration used in PROSPECT

Fiducial volume

Dead segments



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External calibration performance simulation

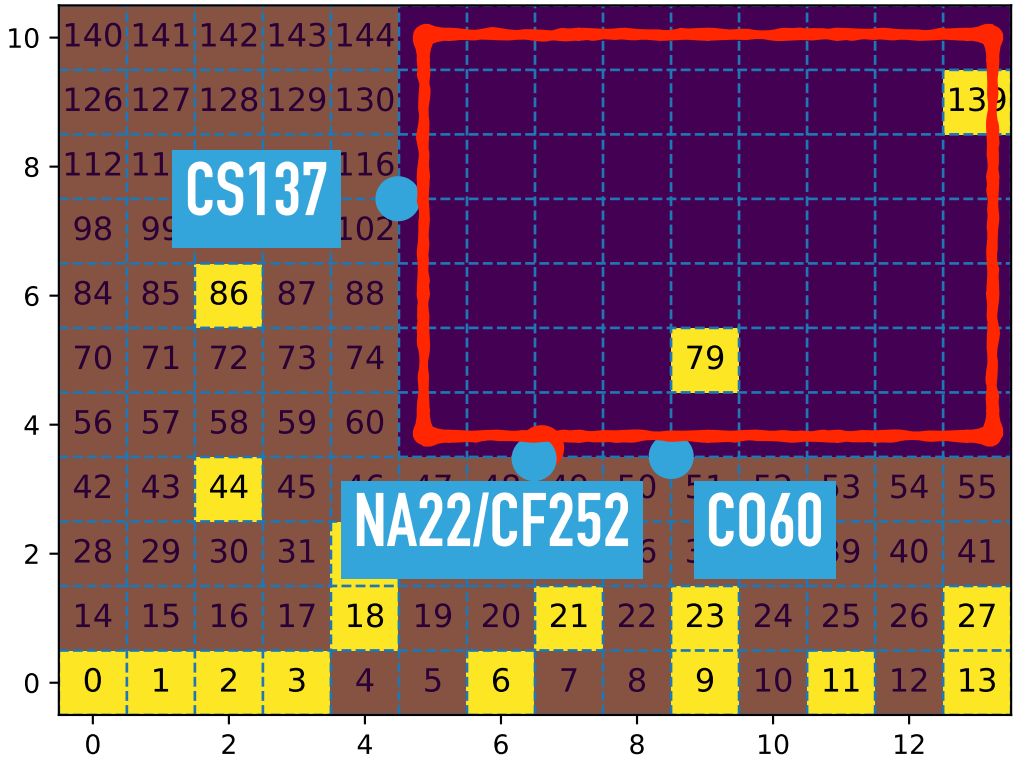
- Manually switch off certain segments in the analysis
- Calibration sources are effectively <1cm outside the fiducial volume

External calibration

Fiducial volume

Dead segments

Manual turned off



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Methodology

- The non-linearity detector response model is not directly simulated via the computational-resource-heavy process of optical photon production and propagation.
- Instead, fractional conversion of true deposited energy to scintillation light is calculated step-by-step during GEANT4 propagation of the particle using parametrization of these physics processes:

$$E_{\mathrm{MC}} = A\sum_i (E_{\mathrm{scint},i}(k_{B2}, k_{B2}) + E_{c,i}(k_C)).$$

Birks' empirical law

$$\frac{dE_{\mathrm{scint}}}{dx} = \frac{\frac{dE}{dx}}{1 + k_{B1}\frac{dE}{dx} + k_{B2}(\frac{dE}{dx})^2},$$

Cherenkov light production

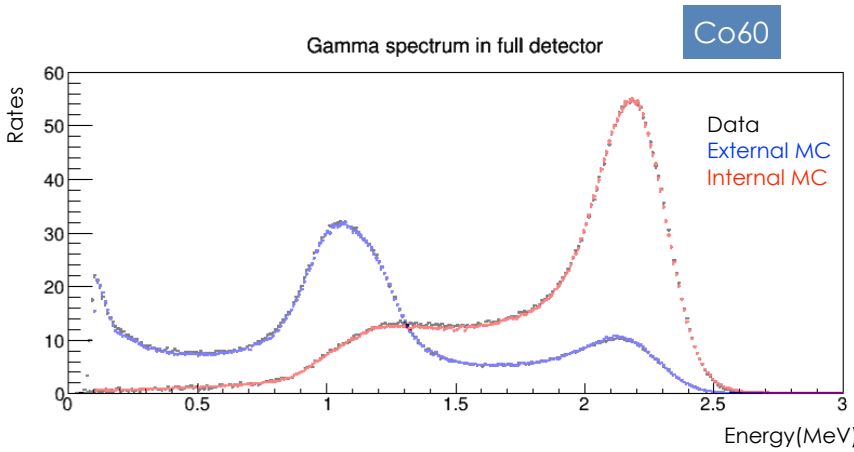
$$E_c = k_c \sum_\lambda N_\lambda E_\lambda,$$

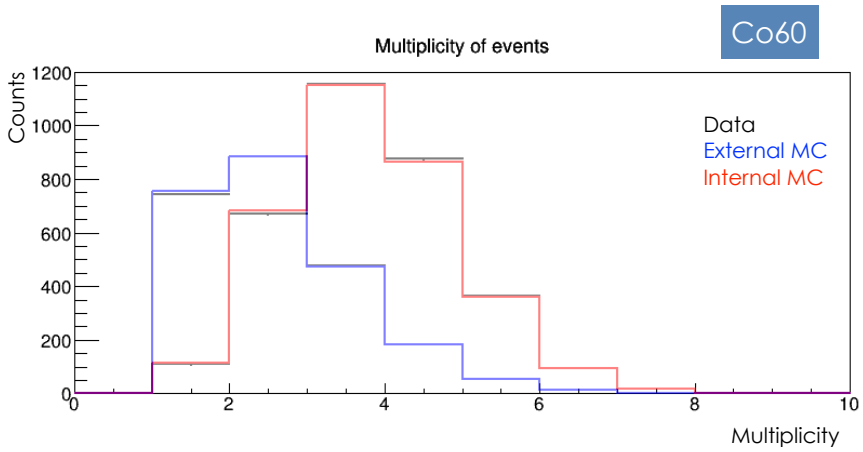
- Best fit response model is determined by minimizing data-MC chi2 for both spectrums and event multiplicity in parameter space (k_{B1}, k_{B2}, k_c)

$$\chi^2_{\mathrm{data-MC}} = \sum_\gamma \chi^2_\gamma + \sum_{\mathrm{multi}} \chi^2_{\mathrm{multi}} + \chi^2_{^{12}\mathrm{B}},$$

Preliminary results

- Both calibration setups show great agreement in spectrum and event multiplicity.





Chi2/ndf =521.97/379(internal) =>575.44/468(external)

- The best fit response models are compatible with each other.

- Quantify how well the model parameters are constrained.

Summary

- PROSPECT-I deploys internal calibration campaign that allows event reconstruction at sub-percent level precision.
- PROSPECT-II detector aims to improve long term stability with simpler and more rigid design.
- This R&D study evaluate the external-source-only performance for PROSPECT-II calibration
- External calibration demonstrates promising performance with simplified P-II geometry that needs more follow-up work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