Status of the COHERENT NaI[Tl] Detector

Samuel Hedges

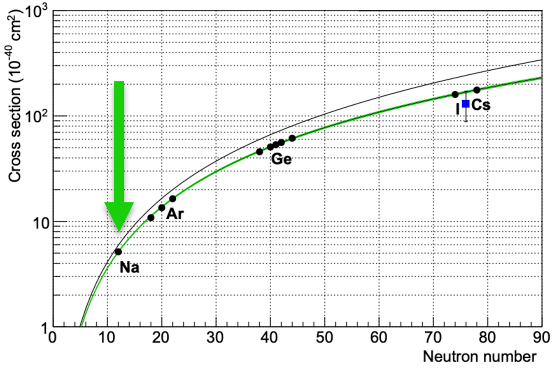
Magnificent CEvNS 2019

11/09/2019

Motivation for a ton-scale NaI[Tl] ν-detector at the SNS

CEvNS N^2 scaling

- CEvNS only recently measured, still testing standard model predictions (N^2)
- ^{23}Na light—low cross section, but energetic recoils



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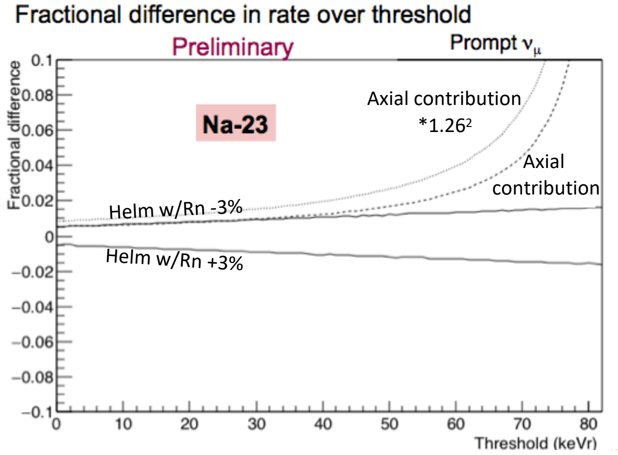

Courtesy of K. Scholberg

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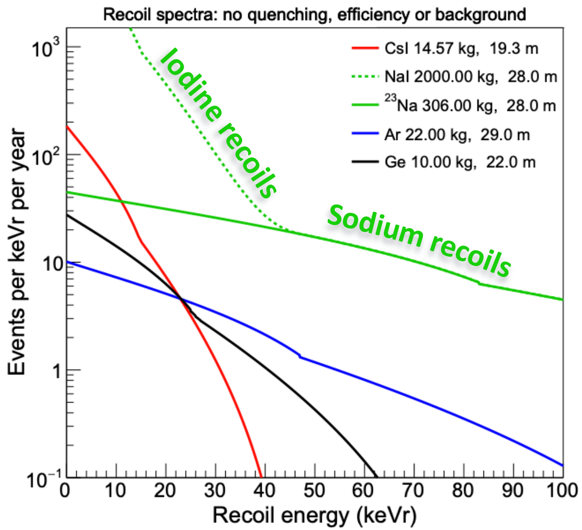
- Measure CEvNS of two nuclei in same detector
- Test results from CsI[Na] measurement



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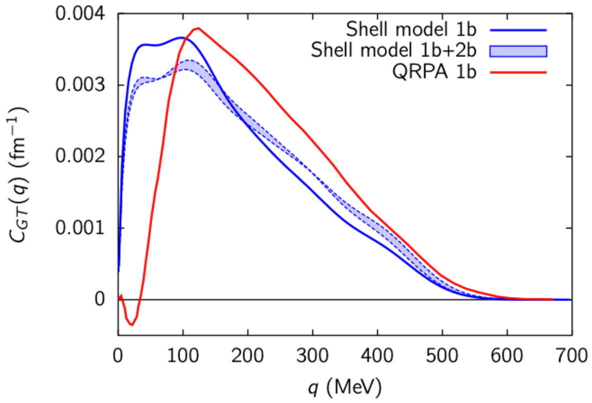
^{127}I charged-current events

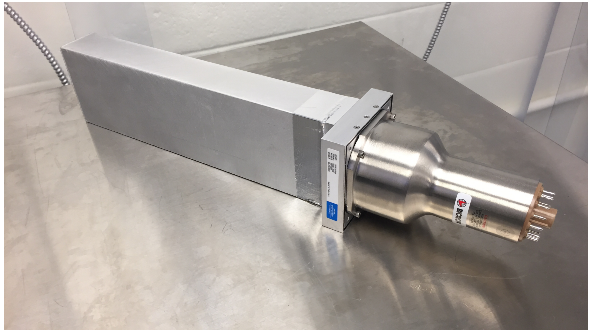
- Can measure electron neutrino charged-current interactions on ^{127}I with same detector
- Test g_A quenching with weak process at intermediate momentum transfer (~30 MeV)



https://arxiv.org/pdf/1610.06548.pdf

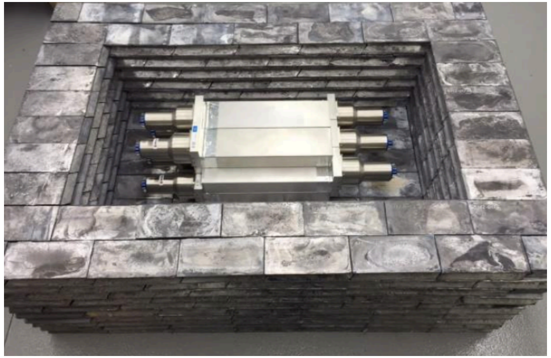
Additional Motivation

- Collaboration has access to 7-9 tons of NaI[Tl] crystals left over from Advanced Spectroscopic Portal program
- Can deploy a several ton detector at modest cost of bases, digitization, high voltage, and shielding
- Free detectors come with drawbacks:
  - Not designed to be low background detectors
  - 10-stage Burle PMTs attached
  - Crystals need to be tested and characterized



Initial Tests—Intrinsic Backgrounds

- Needed to test intrinsic backgrounds
  - Eight crystals tested in a 4” thick lead shield
  - Threshold ~3 keVee
- Reject background events spanning multiple crystals, CEvNS recoils limited to single crystal



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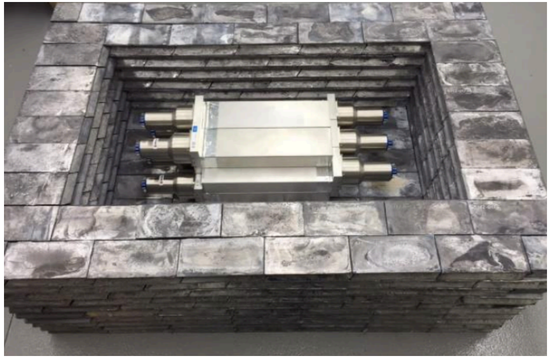
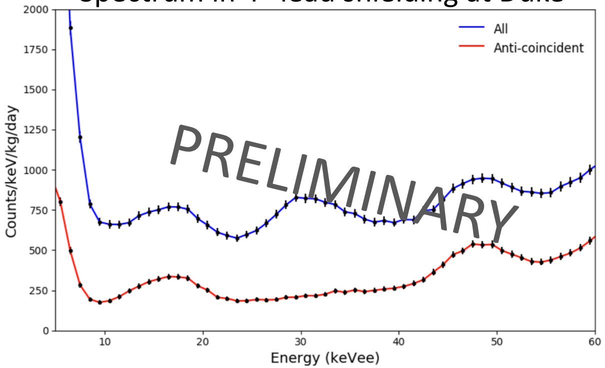
  - Threshold ~3 keVee
- Reject background events spanning multiple crystals, CEvNS recoils limited to single crystal
- Initial measurement saw backgrounds sufficiently low
  - ~200-500 counts/keVee/kg/day in ROI
  - Rejecting coincident events cuts backgrounds ~$^1/_2$
  - Additional rejection of steady-state backgrounds from pulsed beam
    - ~3000x for 5μs window

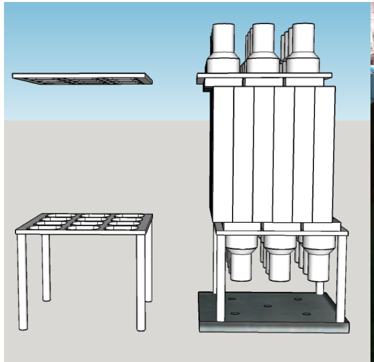


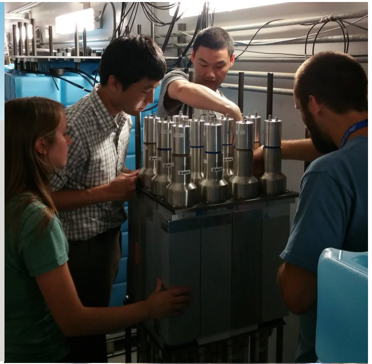
Spectrum in 4” lead shielding at Duke

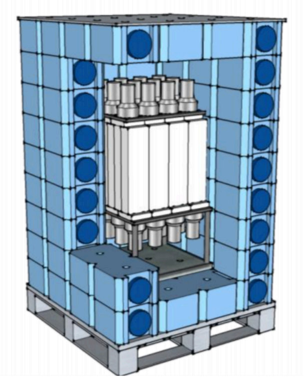


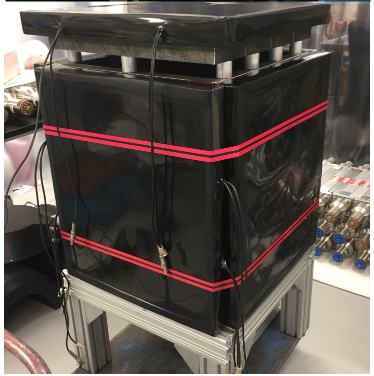
Prototype Detector at the SNS

- Constructed **NaI$\boldsymbol{\nu}$E** (**NaI $\boldsymbol{\nu}$-E**xperiment) detector for further tests at SNS
- Consists of twenty-four 7.7kg NaI[Tl] scintillators (~185kg total)
- Dual-purpose:
  1. Measure in-situ backgrounds for CEvNS
  2. Measure inclusive electron neutrino charged-current cross section on ^{127}I
- Ran in two configurations:
  - 9” water shielding (summer 2016-fall 2017)
  - Iron shielding + vetoes (fall 2017-present)





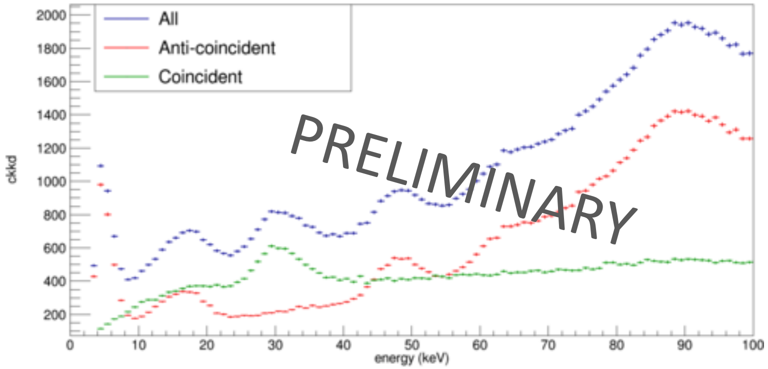




NaIνE Results

- Beam-off backgrounds consistent with initial measurements
  - Self-shielding from outer crystals
  - Muon vetoes gave small improvement after rejecting coincident backgrounds
- Beam-on backgrounds higher due to off-gas pipe in neutrino alley
  - Modest gamma shielding around detector + shielding around pipe
- Charged current analysis ongoing

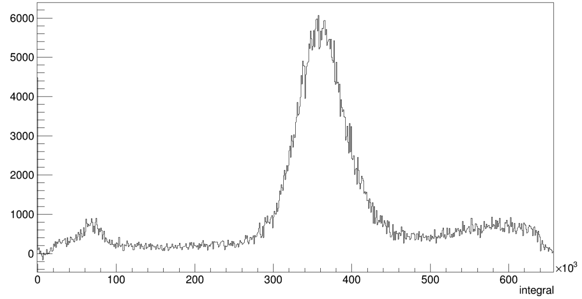
Beam-off spectrum from interior crystal at SNS



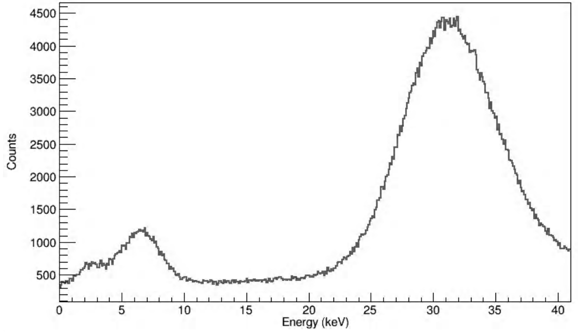
Building a Better Base

- Issues with PMTs:
  - PMTs designed to run up to 1700V, but noisy at high voltages
  - PMTs saturate at high voltages
- Worked with Lorenzo Fabris at ORNL to develop base with built-in amplification, capable of low thresholds at modest voltages
- Two outputs:
  1. CEvNS output: threshold of ~1 keVee
  2. Charged-current output: no saturation up to ~55 MeV
- Completed test production of 18 bases, finalizing design before making more

^{133}Ba data (background-subtracted)

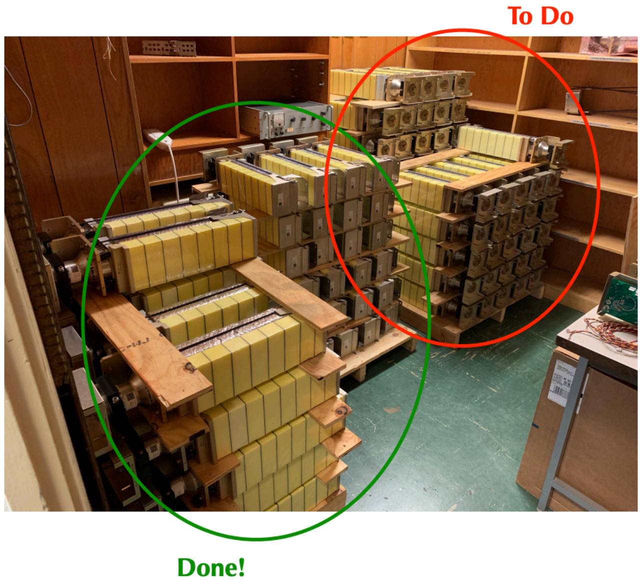


^{133}Ba GEANT4 sim



Crystal Characterization Efforts

- Several hundred crystals needed to be characterized
  - PMT gains, intrinsic crystal backgrounds, geometric response
- Procedure developed by UW group for characterizing crystals running at multiple voltages and scanning source across crystal
- Working on process for measuring internal backgrounds, choose lower background detectors
- Characterization procedure implemented at Duke, still need to start on ORNL crystals
- See poster by Erem Ujah

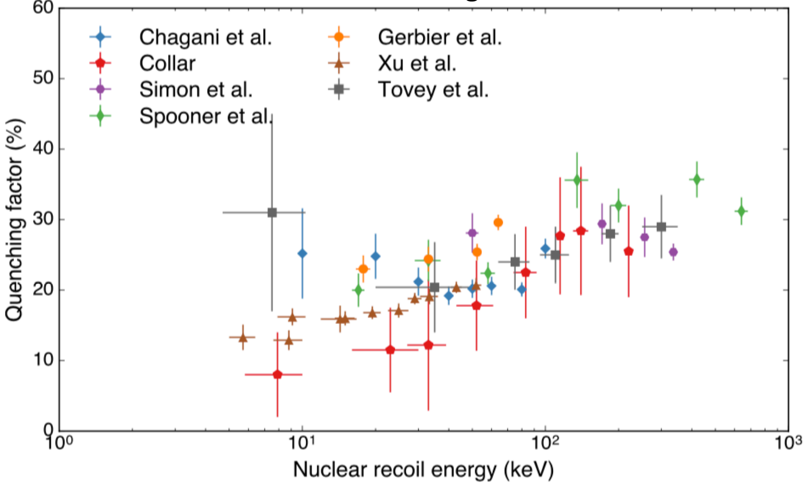


Courtesy of J. Detweiler

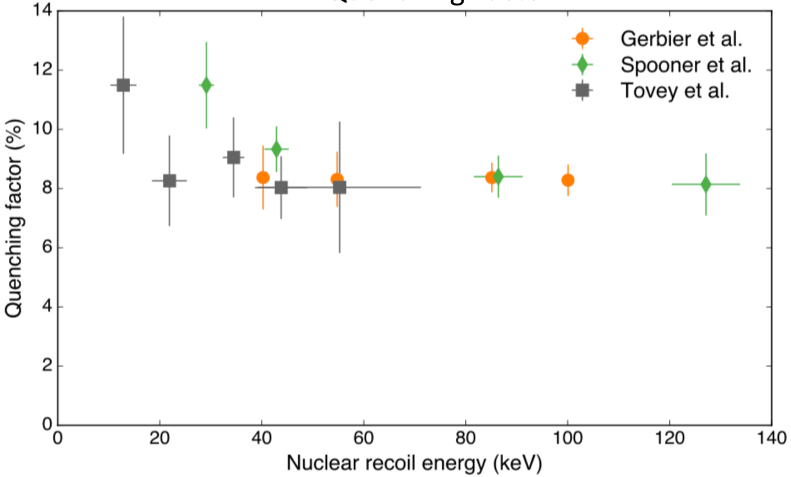
Quenching Factors

- Quenching factors need to be well-known, affect signal above threshold
- Existing measurement of ^{23}Na, ^{127}I QF in NaI[Tl] show some discrepancies in the measurements, want to improve

^{23}Na Quenching Factor



^{127}I Quenching Factor

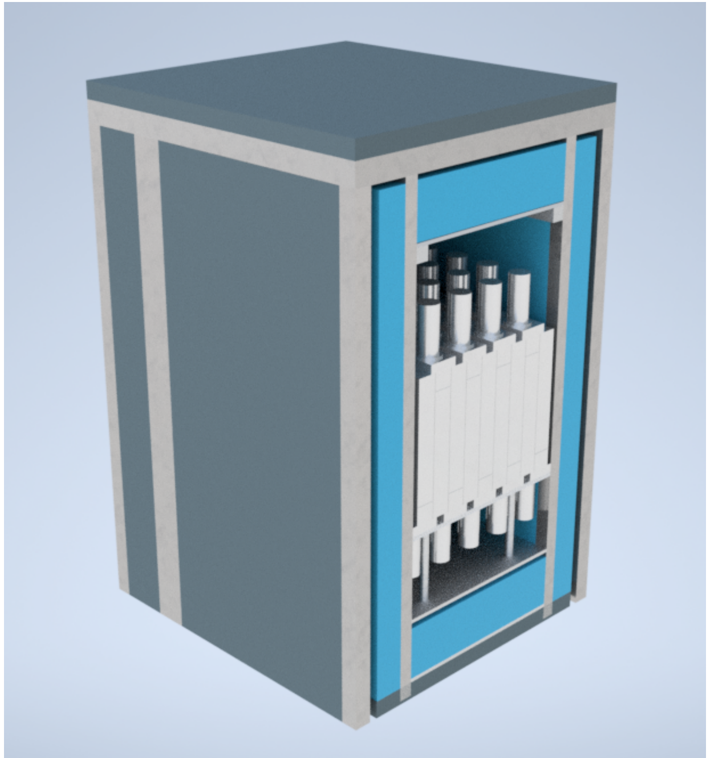


Quenching Factor Measurement at TUNL

- Collaborating with COSINE-100 and ANAIS collaborations
- Measurement completed with several NaI crystals of different sizes and impurities
- 2.7 MeV protons incident on LiF
- 18 liquid scintillator backing detectors, use timing and PSD
- Goal to measure quenching factor down to 1-2 keVee
- Analysis in progress

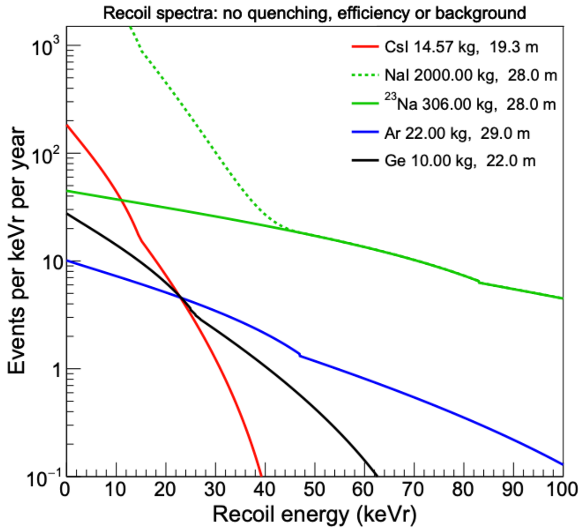
Current Design for Ton-Scale Detector

- Opted for modular design
  - 30”x38”x60”, 485 kg NaI[Tl]
  - 5” of water shielding, 2” of gamma shielding
  - Some detectors to be replaced with plastic scintillator for measuring prompt neutron backgrounds in-situ
- Have on hand DAQ and HV for five modules (2.425 tons)
  - Mass can increase based on total costs and available space



Full-Scale Detector—CEvNS Simulations

- Simulations for 7 modules of NaI[Tl] detectors (~3.4 tons)
  - 13 keVnr threshold for ^{23}Na, above ^{127}I



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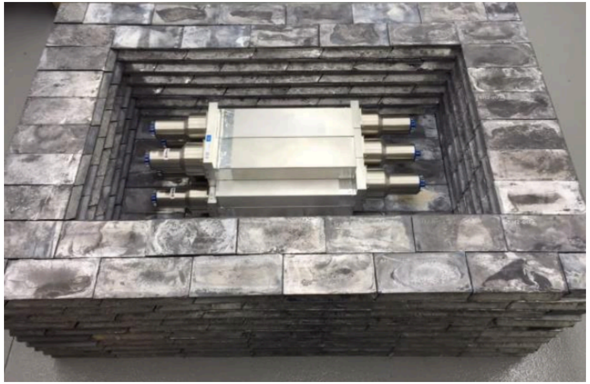

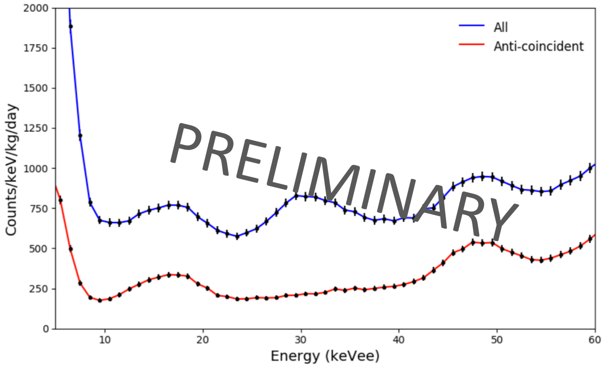

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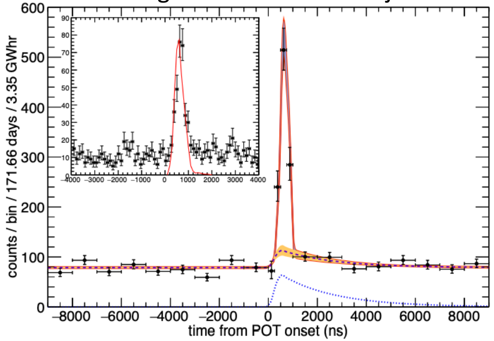
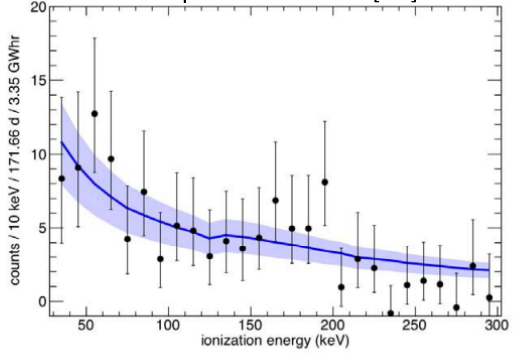
NIN timing distribution from Eljen cell



Prompt neutrons in CsI[Na]



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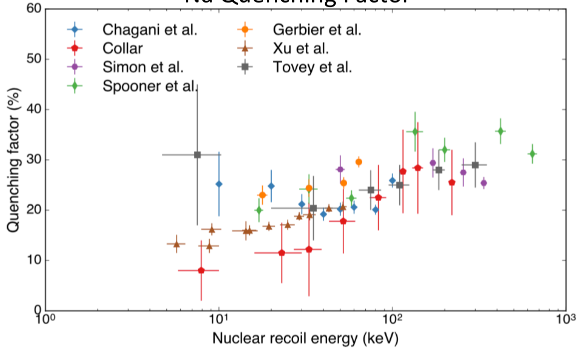

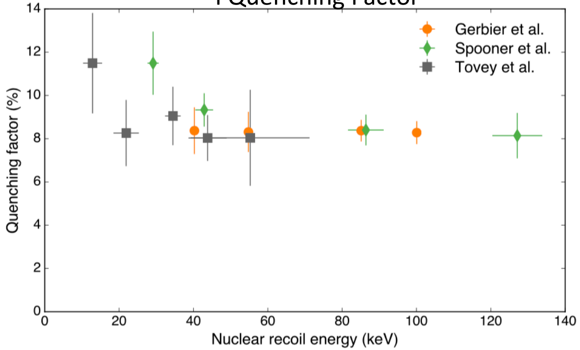

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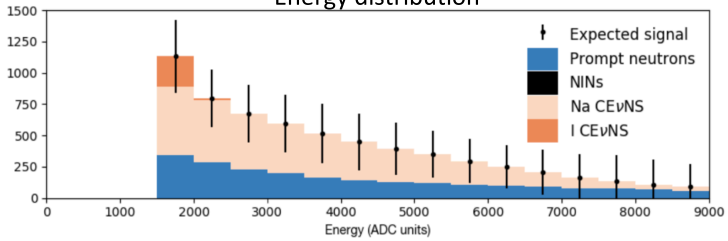
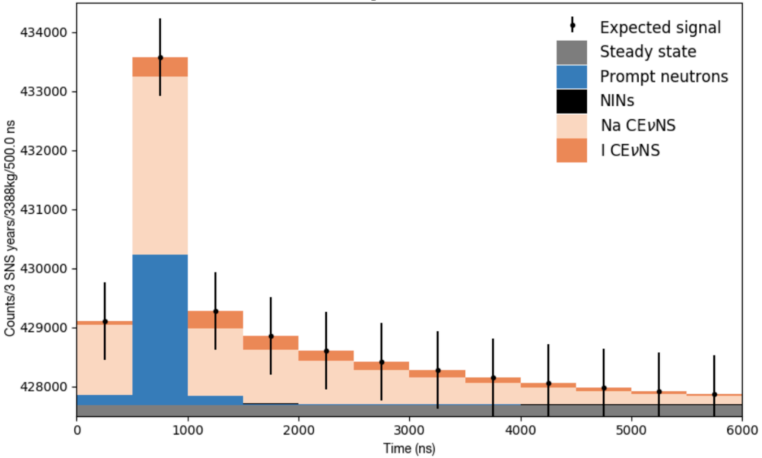
  - Use existing quenching factor data, assume flat in energy region of interest
- Significance of ~3σ/year for ^{23}Na recoils for counting experiment
  - Errors shown are statistical
- Work on improving bases for access to lower-energy ^{127}I recoils, much larger cross section

Energy distribution

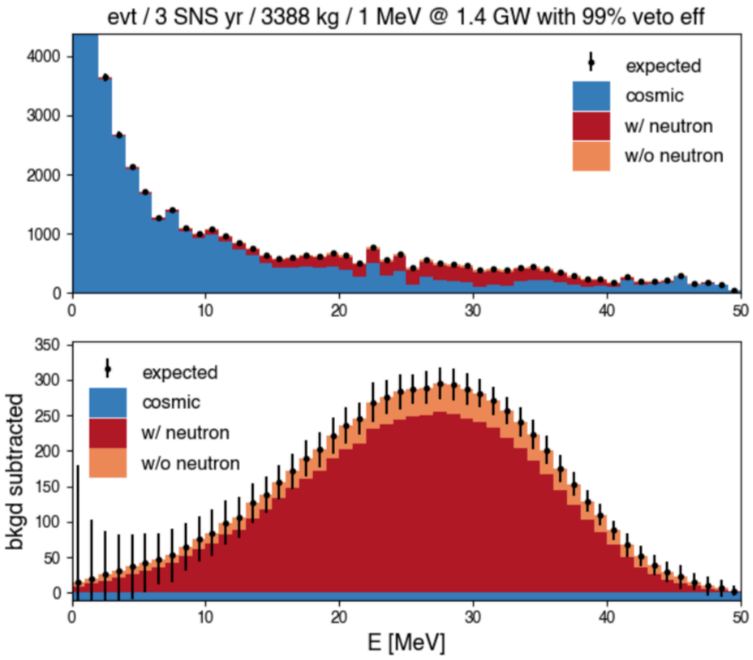


Timing distribution



Full-Scale Detector Simulations—Charged Current

- Charged-current simulations with the same detector
  - Backgrounds from NaIνE prototype
  - Assumed 99% efficient muon veto
  - Charged-current signal simulated in detector using modified version of MARLEY (**M**odel of **A**rgon **R**eaction **L**ow-**E**nergy **Y**ields)
- NaIνE prototype designed to produce initial measurement, full-scale detector would make high-precision measurement, study energy dependence



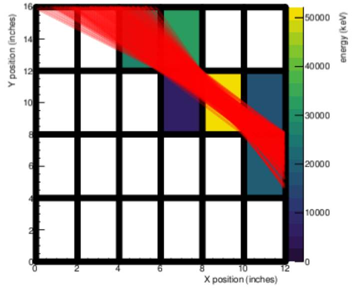
Courtesy of D. Salvat

https://github.com/sjgardiner/marley

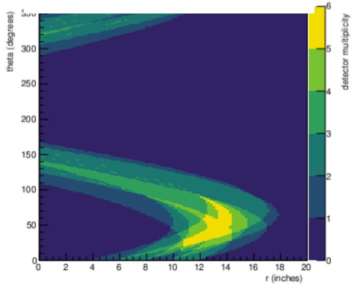
Other Approaches to Identifying Muons

- Muons largest background for charged-current signals
  - Space in shielding limited
  - Vetoes would replace gamma or neutron shielding
  - CEvNS measurement doesn't benefit from vetoes
- Some approaches being investigated:
  - Hough transformation to identify muon tracks
  - Machine-learning approach to distinguish muon and charged-current events, testing simulations with NaIνE data

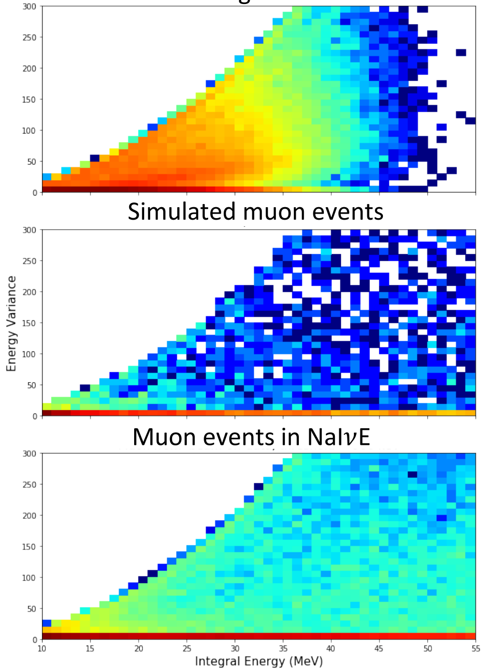
Energy of signals



Hough space



Simulated charged-current events



Courtesy of P. An

Summary

- Ton-scale NaI will allow us to test CEvNS physics and N^2 scaling, study at charged-current interactions
- In preparation for ton-scale detector:
  - Crystal backgrounds studied, manageable
  - Prototype detector deployed to the SNS, collecting data
  - Bases developed for improved thresholds at lower voltages
  - Crystals currently being characterized for detector
  - Quenching factor measurement completed, analysis in progress
  - Finalizing full-scale design to start construction

Acknowledgements

CNEC | Consortium for Nonproliferation Enabling Capabilities

KICP

NNSA National Nuclear Security Administration

NSF

U.S. DEPARTMENT OF ENERGY

THE UNIVERSITY OF CHICAGO

Duke UNIVERSITY

UF UNIVERSITY of FLORIDA

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