Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

“Reactorgenic” neutrino detection using liquid neon

Noble liquids and neutrino coherent scattering

A. Erlandson

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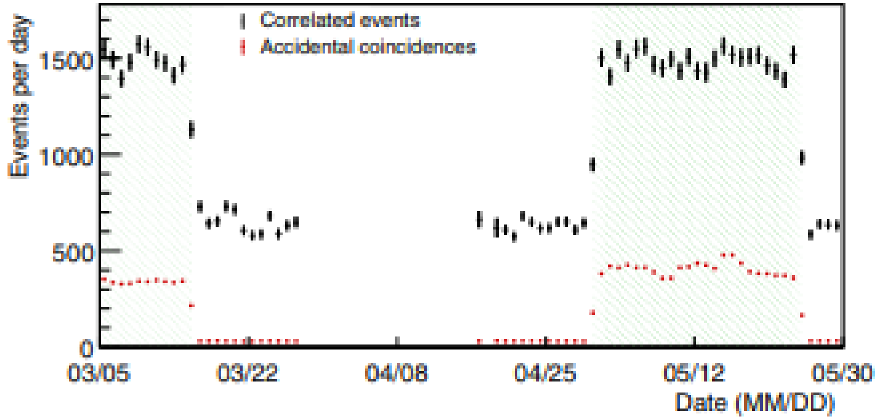
Outline

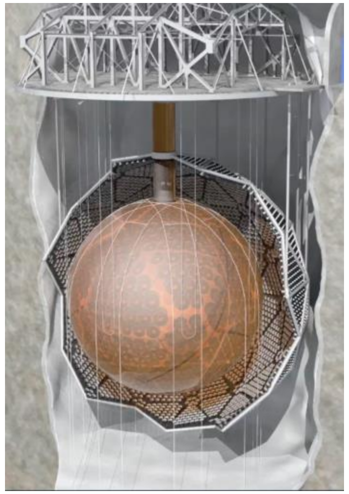
- Reactor monitoring / nuclear non-proliferation
- Neutrinos from CANDU® reactors
- Liquid neon (LNe) detectors: good ideas
- Detector response in Monte Carlo
- LNe as a CEvNS target
- Expected rates from new small modular reactor concepts
- Towards a cross section measurement

Reactor monitoring

- Reactors were the birthplace of experimental neutrino physics (Cowan *et al*, 1956)
  - Inverse beta decay in liquid scintillator detectors has been extensively used to detect “reactorgenic” (trying to coin this term!) neutrinos ever since
  - Driven mainly by fundamental questions (θ_{13}, $|\Delta m^2_{ee}|$)
- Daya Bay, RENO, Double CHOOZ have been hugely successful
- Enabled spin-off applications like antineutrino-based remote monitoring
- With charged current detectors, oscillations must be considered
  - Oscillations don’t matter at all for flavor-blind interactions…
- Aside: SNO+ recently published evidence for reactorgenic neutrinos in their water-phase data with a low threshold. This opens doors for far-field monitoring. See: Phys. Rev. Lett. 130, 091801



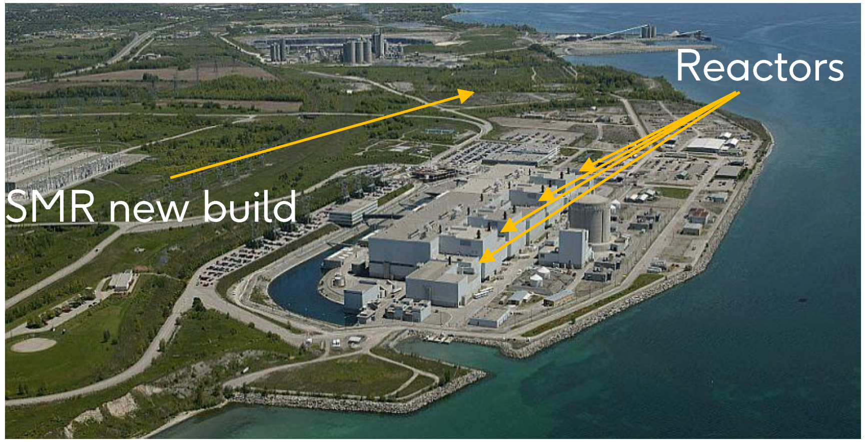
Strong correlation between detected rates and reactor status (on/off) in PROSPECT.
Source: Phys. Rev. Lett. **121**, 251802



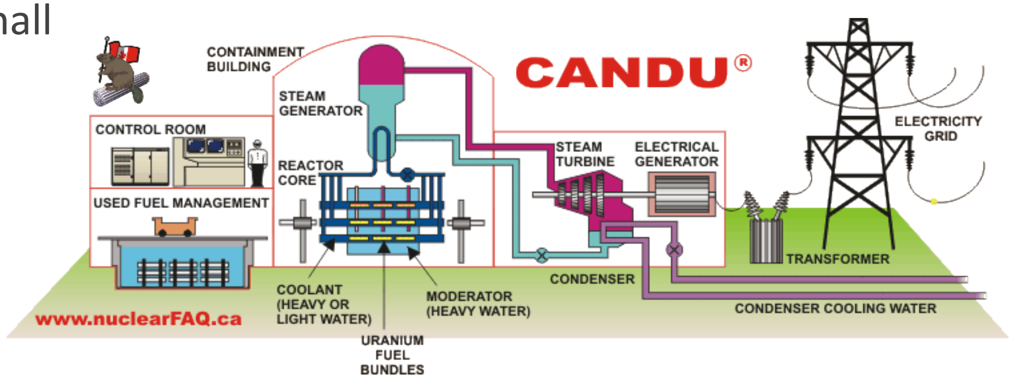
SNO+ detector located 2 km underground and ≥240 km from the nearest reactors.
Source: https://snoplus.phy.queensu.ca/index.html

CANDU reactor neutrinos

- CANDU (CANada Deuterium Uranium) reactors are somewhat different than more common commercial reactors:
  - Natural uranium fuel, online refueling
  - Not long after start up with a fresh core, equilibrium conditions exist
  - Good testbeds for detector characterization
- Light Water Reactors (LWRs) use low enriched uranium and refuel in batches every ~18 months
  - ^{235}U and ^{239}Pu content change a lot more in LWRs – neutrino rate/spectra evolve
  - More ^{235}U boosts neutrino rate
- CANDUs make a decent proxy for the neutrino flux from LWRs and some small modular reactors – at least they serve as a lower limit for the neutrino flux



Darlington Nuclear Generating Station and surrounding areas.
Source: http://www.energyglobalnews.com/construction-of-darlington-nuclear-generating-station-unit-2-completed/



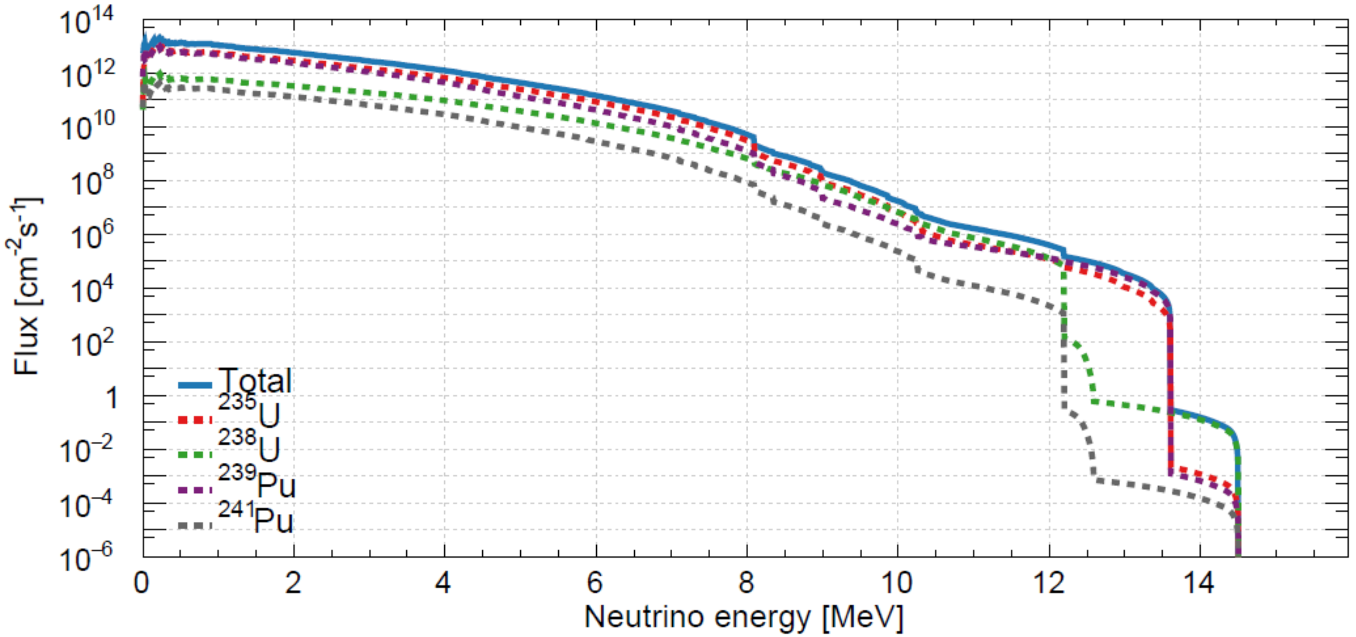
CANDU reactor neutrinos

- Neutrino spectra in reactors driven by 4 isotopes:
- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Simulation tools can predict, given detailed input, the fission fractions and total neutrino production rate
- Neutrino spectra for each isotope obtained from A. C. Hayes
- Constructed a "source term" to normalize the neutrino flux conveniently:

$$\phi = \frac{1.043 \times 10^{12}}{d^{2.007}} \sum_i F_i \;\; [\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MW}_{th}^{-1}]$$

- d in meters

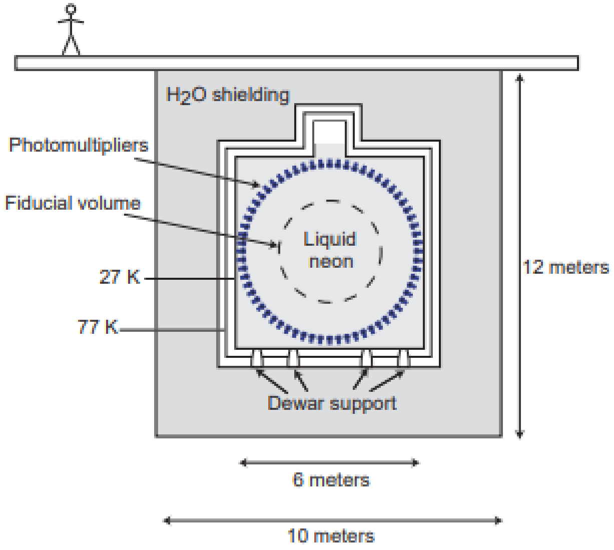
Isotope	Fission Fraction
^{235}U	0.501
^{239}Pu	0.423
^{238}U	0.054
^{241}Pu	0.022



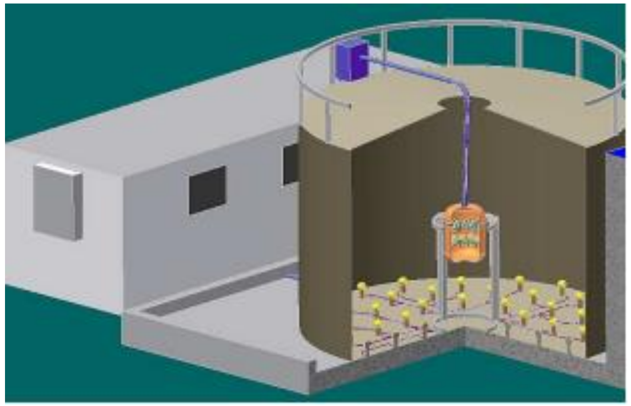
Antineutrino flux at 10 m from a 2.66 GWth CANDU

Liquid neon detectors: good ideas

- The idea of using liquid neon to detect nuclear recoils goes back ~20 years:
  - Cryogenic Low Energy Astrophysics with Noble gases (CLEAN) [Horowitz *et. al*]
  - Coherent Low Energy A Recoils (CLEAR) [Scholberg *et al*]



CLEAN



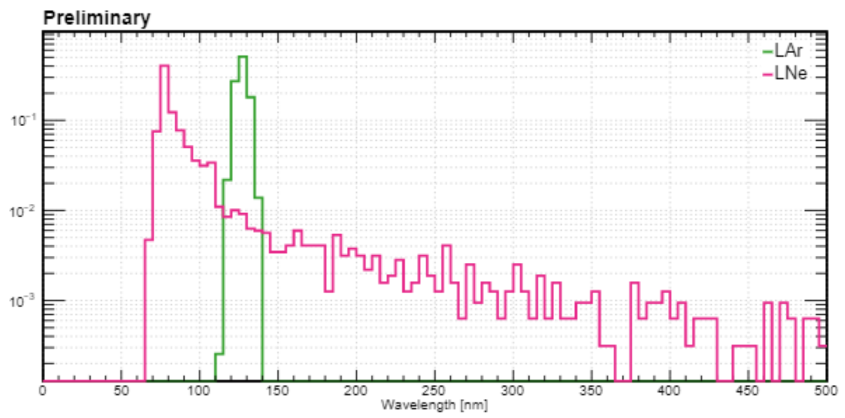
CLEAR

arXiv:0910.1989v2

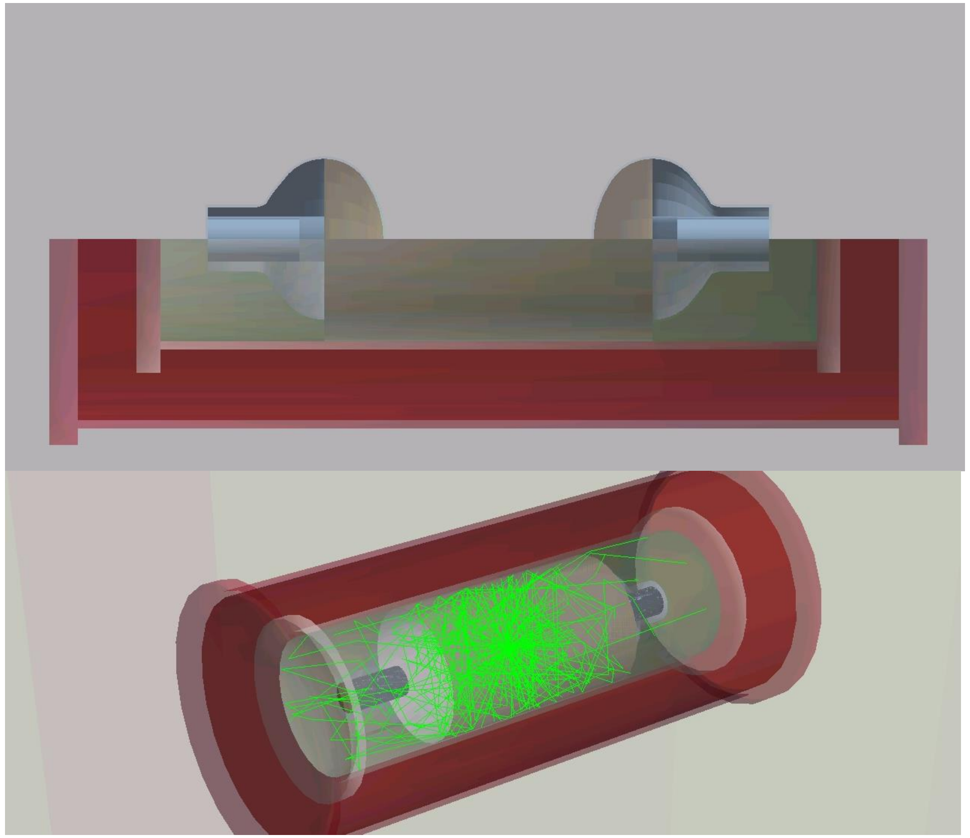
- CLEAN side of DEAP/CLEAN developed the MicroCLEAN detector which has successfully used LNe in "conventional" hardware
  - MiniCLEAN could have done a LNe run had things worked out…
- CLEAR morphed into a broader physics program you might have heard of called COHERENT
  - CENNS-10 is based on verified designs
- Neon hasn't gotten much attention in recent years

Detector simulation

- Using a reasonably robust simulation tool (RAT), a response model can be constructed
  - Simulate micro-physics down to individual optical photons
  - Includes full optical model
  - Includes simulation of DEAP-3600 data acquisition system (DAQ)
  - MC DAQ simulation validated with data from DEAP-3600
    - Source: https://doi.org/10.22215/etd/2019-13705
- Overall detector concept is intentionally similar to MicroCLEAN/CENNS-10 because these concepts work in practice



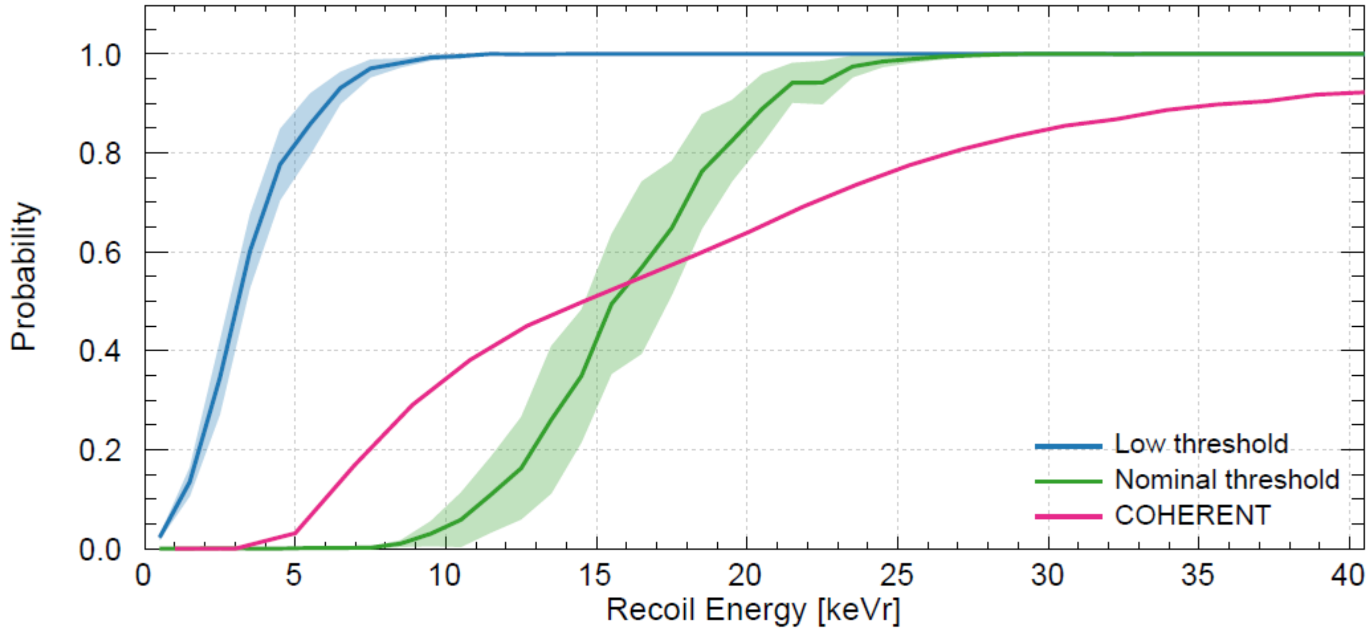
Scintillation spectra in RAT for LAr and LNe



Top: cut away of the detector
Bottom: photon bomb simulation

Detector simulation

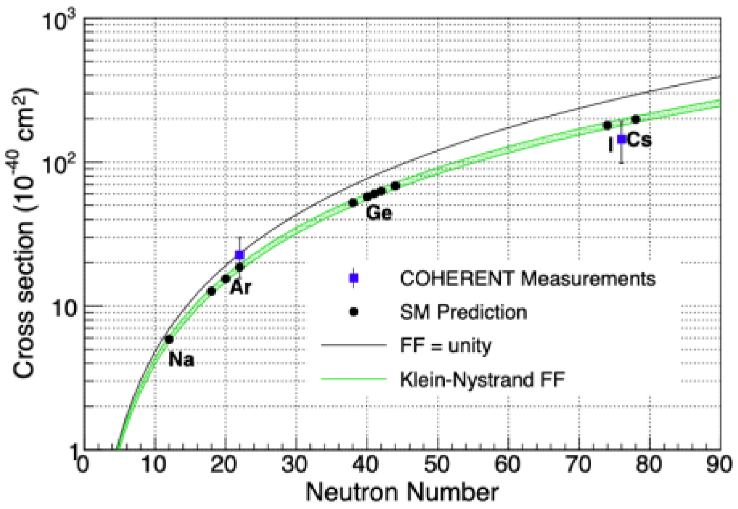
- Important output from the simulation is the trigger efficiency curve
- Simulations of ^{20}Ne and ^{40}Ar nuclear recoils
- Let the DAQ simulation determine whether the detector would trigger given E_r



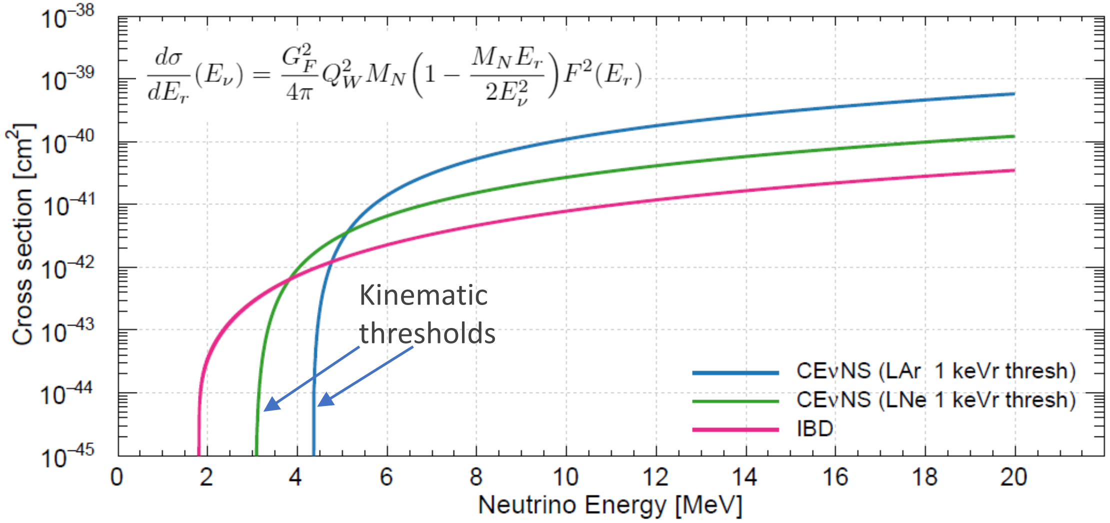
- Uncertainties result from different responses due to the target
- COHERENT's curve includes selection cuts and isn't geared towards really low energy recoils
  Source: https://doi.org/10.5281/zenodo.3903810
- "Low" and "Nominal" models use settings validated with DEAP-3600 data

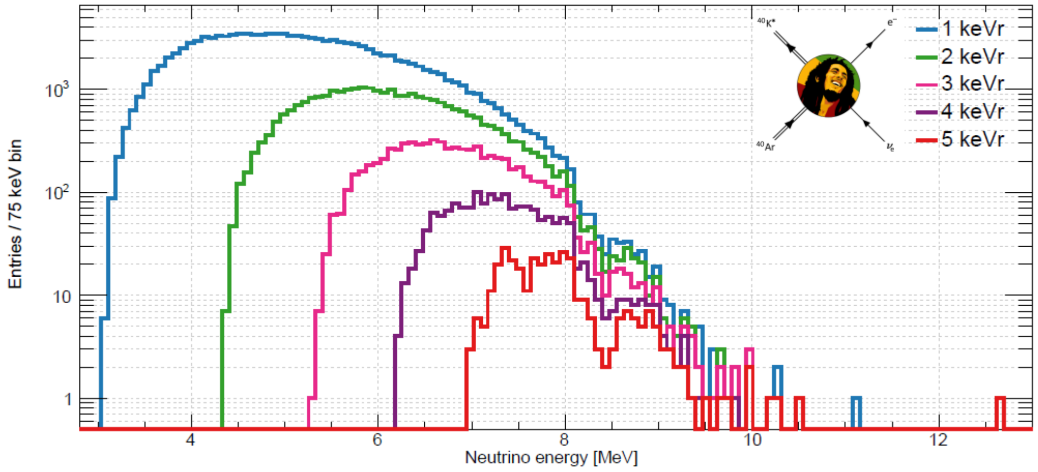
Liquid neon CEvNS

- Like liquid argon, neon is a bright scintillator
- MicroCLEAN demonstrated that a target exchange experiment is feasible
- Sure, the XS is smaller for LNe, but the kinematics is favourable
  - This is especially true for low energy (reactorgenic) neutrinos



Flux averaged cross section using the SNS spectrum. Source: Scholberg, INSS lecture, 2021





MARLEY v1.2.0 used to simulate CEvNS final states given the CANDU neutrino spectrum.

- Straight forward to obtain cross sections
- Low thresholds required for LNe/LAr detectors to be advantageous
  See: PHYS. REV. D 102, 053008 (2020)

CEvNS rates from reactors

- Assuming LEU reactor neutrino flux is reasonably approximated by CANDU
  - This is somewhat a conservative "worst case" scenario but safer than assuming 100% ^{235}U
  - Not totally trivial to model small modular reactor (SMR) fuel behavior in some cases

Reactor	Type (fuel)	Power [MW_{th}]	Flux [$cm^{-2}s^{-1}$]
CANDU [21]	Heavy water (NU)	2660	2.73×10^{13}
NuScale [22]	Light water (LEU)	924	9.48×10^{12}
Terrestrial Energy [23]	Molten salt (LEU)	884	9.07×10^{12}
GE-Hitachi [24]	Light water (LEU)	870	8.92×10^{12}
USNC [25]	Gas cooled (LEU)	15	1.54×10^{11}

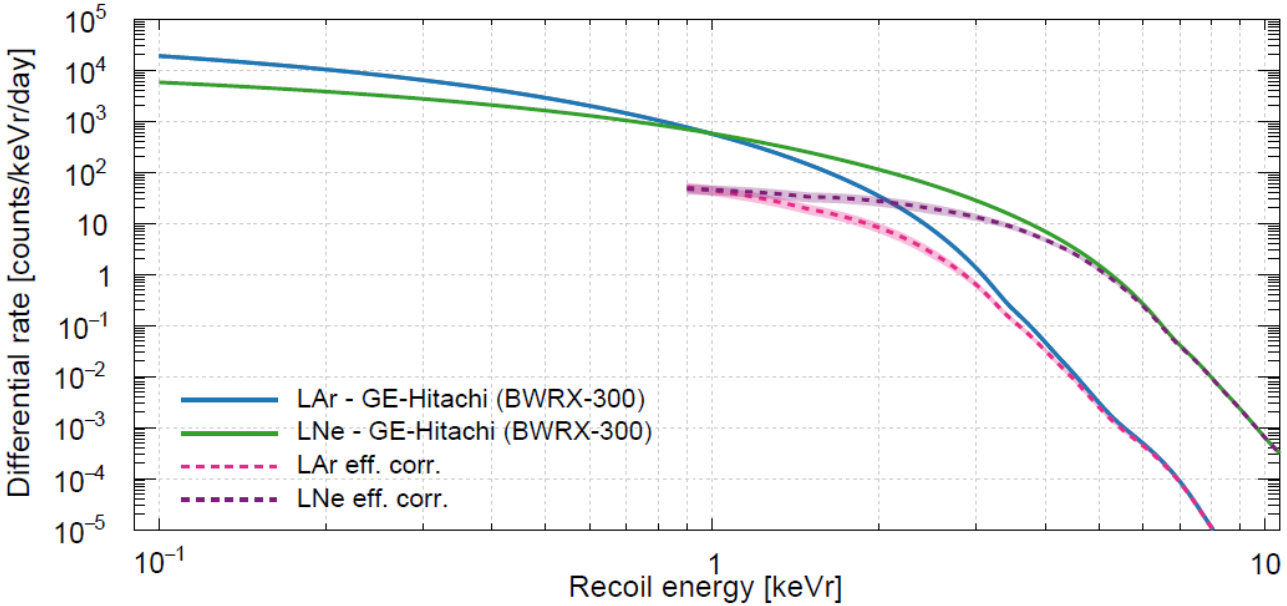
- Fluxes computed assuming 10 m stand-off distance
  - 10 m isn't really practical for massive commercial reactors like CANDU but might be possible for SMRs

CEvNS rates from reactors

- Convenient to work in with differential recoil rates

$$\frac{dR}{dE_r} = \int dE_\nu \phi_\nu(E_\nu) \frac{d\sigma}{dE_r}(E_\nu)$$

- Can easily include detector response constraints in this space
- Due to kinematics, neon is less sensitive to the threshold
- Detector response eats 77%-90% of the rates

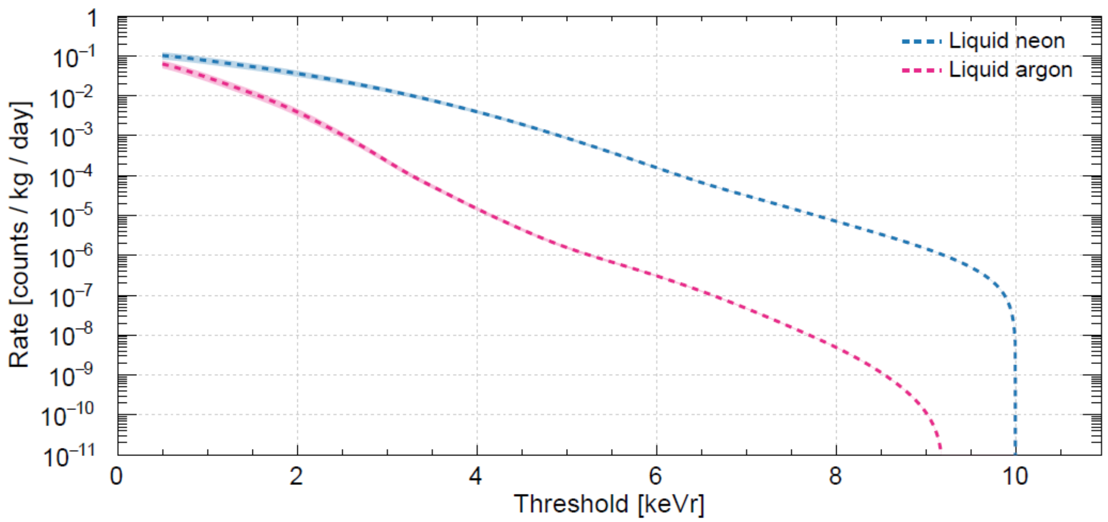


Reactor	LNe (uncorrected)	LNe (corrected)	LAr (uncorrected)	LAr (corrected)
CANDU©	1086	243 ± 49	609	60 ± 12
NuScale	377	84 ± 17	211	21.0 ± 4.2
Terrestrial Energy	361	81 ± 16	202	20.1 ± 4.0
Ge-Hitachi	355	79 ± 16	199	19.8 ± 4.0
USNC	6	1.37 ± 0.27	$\ll 0.01$	$\ll 0.01$

Rates [events/day] for LNe and LAr computed assuming 100 kg detector placed 10 m from each reactor with a 1 keVr threshold. Uncorrected rates do not include detector effects while corrected rates do. See figure at top right.

CEvNS rates from reactors

- LNe gives you more leeway in the detector threshold
  - This is good because low thresholds in scintillation detectors are very hard to obtain
  - PMT noise will be a barrier
  - Newer technologies like SiPMs might be the path forward
- LNe turns out to be 4x more sensitive than LAr in this application

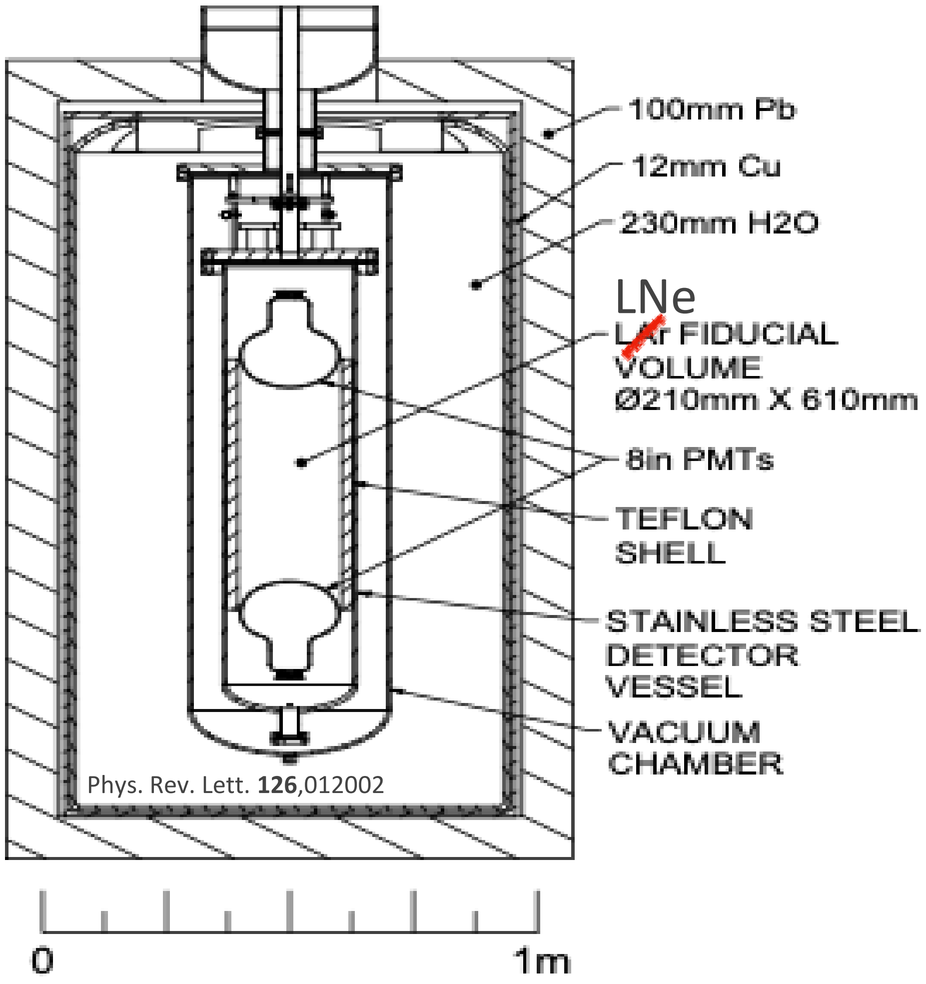


Rates as a function of the detector threshold for LNe and LAr. Here, we've used a 100 MWth reactor and 10 m distance.

- Comparing this work to Bowen & Huber's (PHYSICAL REVIEW D 102, 053008 (2020)) we find some discrepancies
  - Eg: B & H predict 0.81 events / day / kg for LNe 10 m from a 100 MWth (^{235}U reactor) with a 1 keVr threshold
  - We predict 0.41 events / day / kg before factoring in detector response
  - Differences dominated by neutrino flux normalization followed by the calculation of the differential cross section
    - We included the nuclear form factor but it's a pretty small correction
- Regardless, event rates with the right conditions are still practical

Towards a cross section measurement

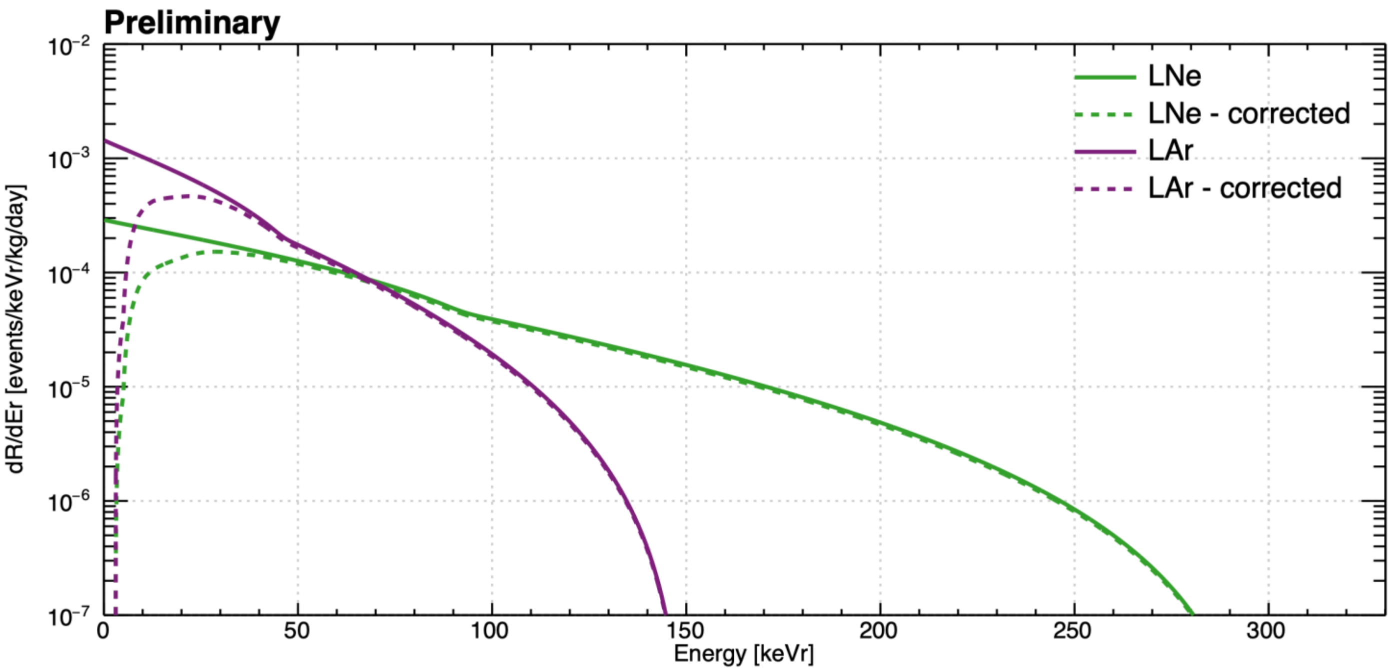
- No measurement of the CEvNS cross section exists for neon
    - Required input to all calculations using LNe
    - Deviations from SM prediction would be interesting (possible useful if XS was higher)
    - Not many options to procure a measurement like this
- Solution: We are exploring the possibility of a target exchange experiment in CENNS-10 with COHERENT
    - Benefit: nearly identical backgrounds (minus ^{39}Ar) and detector systematics
    - Benefit: shielding and proximity to the SNS
    - Benefit: soon-to-be improved uncertainty on the SNS neutrino flux
    - Cost: Neon is tragically expensive right now



Phys. Rev. Lett. **126**,012002

Towards a cross section measurement

- Some quick calculations show that a LNe target in CENNS-10 would produce reasonable rates
- Requires comparable exposure to CENNS-10 LAr measurement
  - Mass of neon in CENNS-10 would be ~20 kg



- Assumed the time-averaged SNS flux is $1.64 \times 10^7\ \nu/cm^2/s$
- Integrate differential spectrum above 1 keVr

Target	Theory	Experiment
Liquid argon	317.8	172.4
Liquid neon	117.3	84.7
Ratio	36.91%	49.13%

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Final remarks

- Up and coming SMR technology requires some new approaches to ensure nuclear non-proliferation
- CEvNS technology may be well suited for this application
- Noble liquid detectors can scale to large masses
- Neon out performs argon in this context by a factor of 4
- All of this is moot without a cross section measurement and COHERENT is best positioned to do this
- SMR deployments in both Canada and the US are imminent