Coherent Elastic Neutrino Nucleus Scattering as a Probe to Study Reactor Antineutrino Fluxes and Spectra

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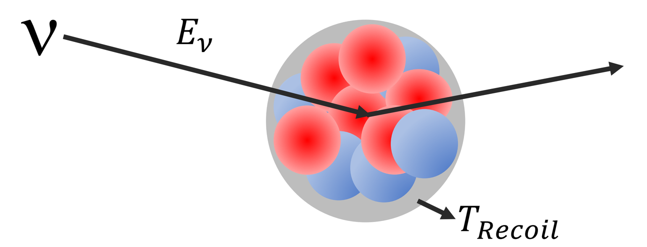
CEvNS Process (1)

Neutral current process **first predicted in 1974**

- Insensitive to ν flavor
- No threshold
- With E ≲ 50 MeV, ν sees entire nucleus rather than individual nucleons
  - Cross section proportional to N^2
  - Boost up to a factor of 1000 with respect to inverse beta decay (IBD)
- Complementary to IBD for detection of reactor neutrinos

Target Nucleus	T_{Max}: $E_\nu \approx$ 3 MeV	T_{Max}: $E_\nu \approx$ 30 MeV
Ar	484 eV	48.3 keV
Zn	296 eV	29.5 keV
Ge	266 eV	26.6 keV
	(Reactor)	(SNS)



…. But low recoil energy: Experimental challenge (hard to discriminate against backgrounds). **First detection in 2017 at SNS by COHERENT[1].**

Current efforts focus on CEvNS at nuclear reactors: Bolometers provide ≲ 100 eV thresholds suitable for reactor $\bar{\nu}_e$ detection!

Sensitivity Study Methods (3)

Reactor ν spectra model

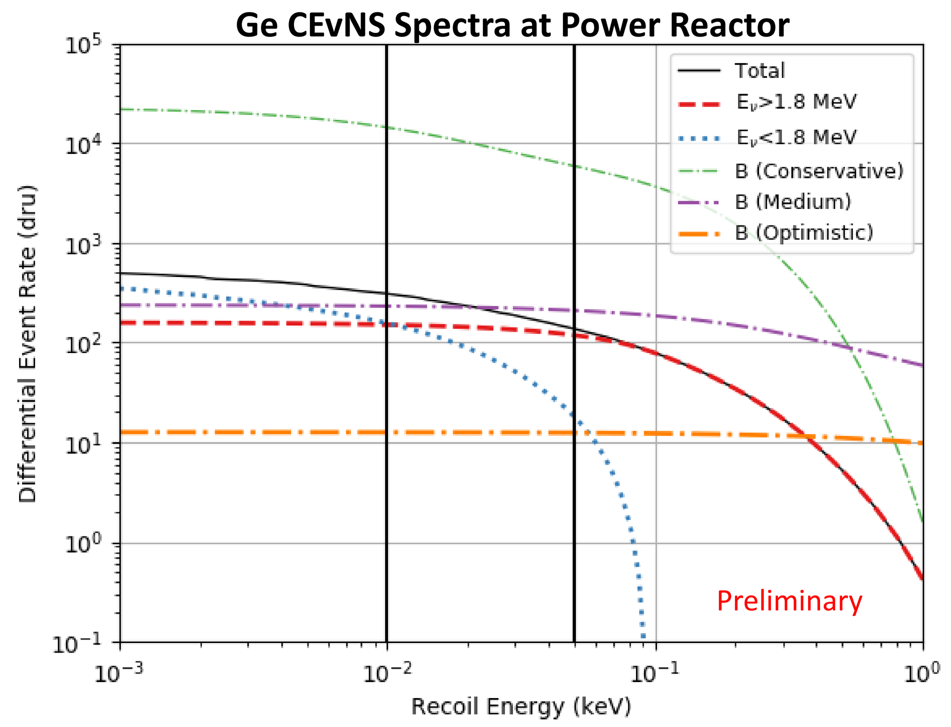
- 2 Reactor models (Fuel Inventory → APOLLO2/DARWIN3 codes)
  - Power Reactor (^{235,238}U, ^{239,241}Pu mix): 60 m @ 4.25 GW
  - Research Reactor (pure ^{235}U): 7 m @ 50 MW
  - ν spectra library → BESTIOLE[2]

Bolometer Detectors & Background Assumptions

- Si, Zn, Ge, Al_2O_3, $CaWO_4$
- 3 background models

Scenario	T_{Thr} (eV)	Back. shape	Back. rate (evts/kg/day)
Best	1	Optimistic (~Flat)	10
Med	10	Medium (Exponential)	100
Worst	50	Conservative (CEvNS-like)	1000

Ge CEvNS Spectra at Power Reactor



Sensitivities calculated with frequentist likelihood-based approach

Parameters of Interest — Observed Counts — Background Counts (σ_{back} = 10%)

$$\mathcal{L}(\mathbf{D}|\theta,\psi) = \mathcal{L}(\psi) \times \prod_i^{N_{bins}} P\left(N_{obs}^{(i)} \middle| N_{sig}^{(i)}(\theta) + N_{bg}^{(i)}(\psi)\right)$$

(no shape uncertainty)

Nuisance Parameters — Signal Counts (σ_ϕ= 5%)

CEvNS Applied to Reactor $\bar{\nu}_e$ (2)

Reactor $\bar{\nu}_e$: β^- decay of fission products in nuclear fuel from fission of **^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu (power reactor) or ^{235}U (research reactor)** + β^- decay of **activated isotopes in fuel or structural material**

Most commonly detected through IBD:

- Clear $\bar{\nu}_e$ signature. Suitable for reactor flux rate & shape characterisation, and the study of neutrino oscillations

…But: - Low cross-section & energy threshold (E_{Th} = 1.8 MeV)
- Rate and shape anomalies between measurements and predictions

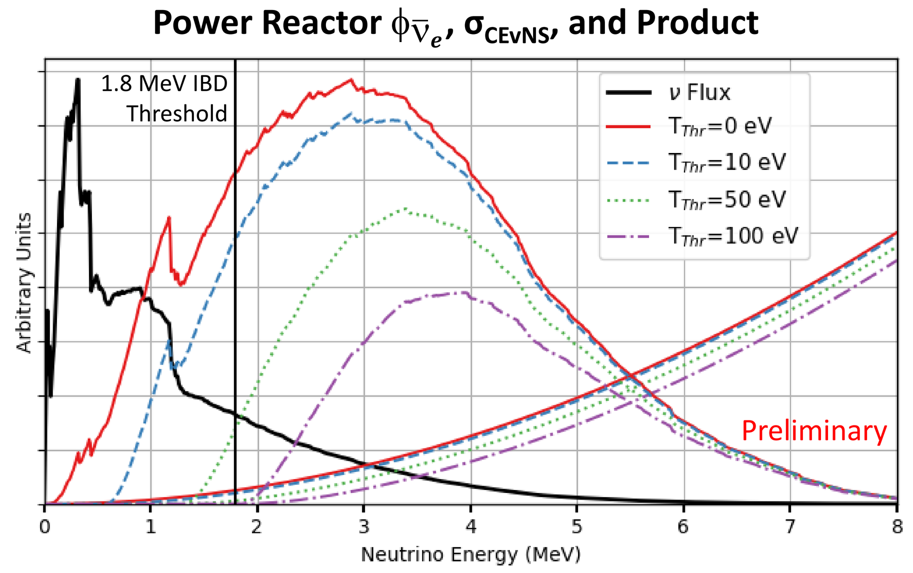
High CEvNS Physics Potential:

- Non-Standard Neutrino Interactions
- Neutrino Electromagnetic Properties
- Low Energy SM Tests

⇒ CEvNS: New detection channel with access to low energies

power reactor	IBD: H	CEvNS: Al_2O_3	Si	Zn	Ge	$CaWO_4$
⟨σ⟩ [10^{-43}cm²/fission], $T_{Thr = 10\ eV}$	~6	~100	~150	~870	~1100	~4500
⟨σ⟩ [10^{-43}cm²/fission], $T_{Thr = 100\ eV}$		~70	~100	~410	~510	~890

Power Reactor $\phi_{\bar{\nu}_e}$, σ_{CEvNS}, and Product



Selection of planned experiments using reactor $\bar{\nu}_e$ source:

Name	$T_{Threshold}$ [eV_{NR}]	Payload [kg]	Baseline [m]	Thermal Power	ν Flux [cm⁻² s⁻¹]	Over-burden [m.w.e.]
MINER	100	10	2-5	1 MW	4 x 10^{11}	15
NUCLEUS	10	0.01/1	60	4.25 GW	3 x 10^{12}	≤4
Ricochet	50/10	~1.3	8	60 MW	10^{12}	≈15

This poster: CEvNS sensitivity to reactor spectrum features
- Neutrinos below 1.8 MeV
- Neutrinos from non-fission processes
- Shape distortions observed by IDB experiments

Sensitivity to Low Energy Neutrinos (4)

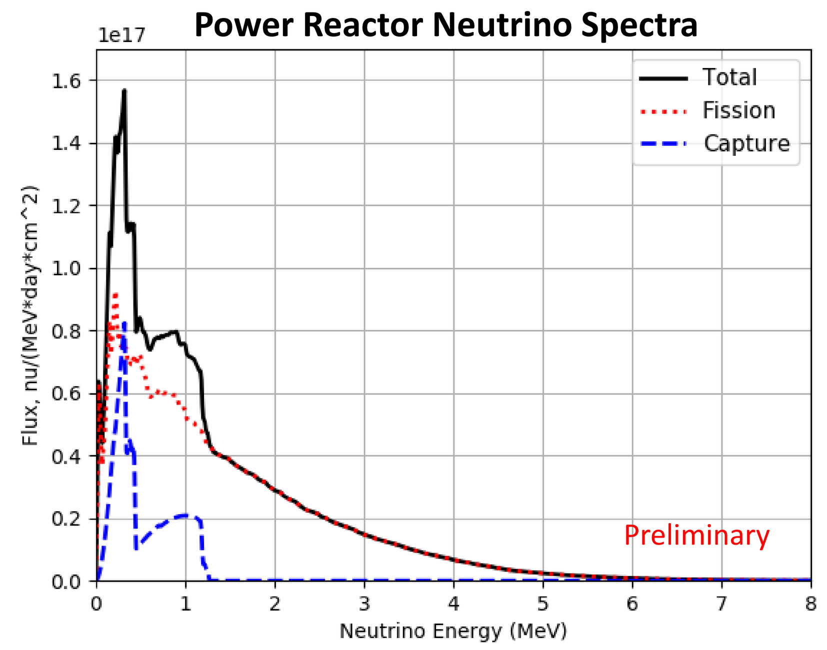
Below 1.8 MeV (IBD threshold), $\bar{\nu}_e$ from:

- Fission
- Neutron capture on structural materials
- Neutron capture on fuel (^{238}U):

$$^{238}U + n \rightarrow {}^{239}U \xrightarrow{\beta^-:\,1.26\,MeV} \bar{\nu} + e^- + {}^{239}Np \xrightarrow{\beta^-:\,0.7\,MeV} \bar{\nu} + e^- + {}^{239}Pu$$

Power Reactor: - ~75% of $\phi_{\bar{\nu}_e}$ is below 1.8MeV
- ~18% of $\phi_{\bar{\nu}_e}$ from n-capture (82% from fission)
- n-capture on structural materials is negligible

Research Reactor: - n-capture on fuel is negligible
- n-capture on structural materials neglected
- Detection of E_ν < 1.8 requires ~2x the exposure



Sensitivity to $\bar{\nu}_e$ with E_ν < 1.8 MeV (preliminary)

[kg*yrs]	Al_2O_3	Si	Zn	Ge	$CaWO_4$
Best	0.17	0.11	0.04	0.04	0.05
Med	2.1	1.3	0.31	0.27	1.3
Worst	230.	190.	190.	270.	5.6e3

Sensitivity to $\bar{\nu}_e$ from ^{238}U n-capture chain (preliminary)

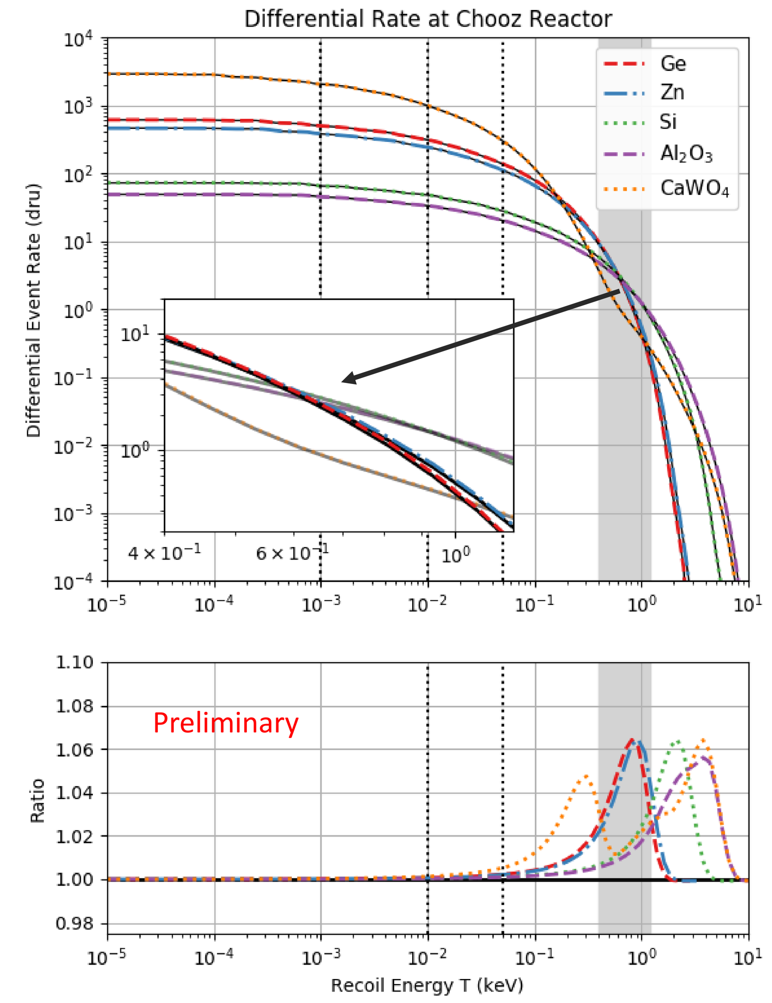
[kg*yrs]	Al_2O_3	Si	Zn	Ge	$CaWO_4$
Best	17.	12.	5.2	4.9	7.9
Med	190.	150.	90.	94.	3.2e3
Worst	2.8e4	2.9e4	4.8e6	2.7e5	4.1e6

Exposure for **Power Reactor** such that **50%** of experiments reach **5σ** significance

⇒ Detection is difficult (low recoil threshold required), but may be possible with upcoming bolometric experiments

Sensitivity to Reactor Spectral Shape (5)

- Measured[3] and predicted[2,4] IBD spectra are not compatible within reported uncertainties
- Shape discrepancy: excess of events around 5 MeV ("bump") and deficit below
- Model as Gaussian function [μ = 5.7 MeV, σ = 0.6 MeV] with amplitude selected to best match data



$\bar{\nu}_e$ spectrum is strongly washed out in recoil energy

- Modification to bump spectrum extremely small
- Total Rate increases ~ 1% due to $\sigma \sim E^2$ scaling
- Narrower bump makes detection easier
  - $CaWO_4$ bump has more structure, but is hard to detect because it is very washed out

Sensitivity to Reactor Shape Distortion (preliminary)

[kg*yrs]	Al_2O_3	Si	Zn	Ge	$CaWO_4$
Best	8.2 x 10^4	770.	50.	40.	280.

Exposure for **Power Reactor** such that **50%** of experiments reach **5σ** significance

⇒ Detection is beyond upcoming experiments

Conclusions (6)

- **Detection of $\bar{\nu}_e$ with E_ν < 1.8 MeV is possible** with upcoming bolometer experiments
  - **Low thresholds (O[<10 eV])** crucial
  - At low thresholds, **Zn/Ge** are best due to high σ and more favorable E_ν > 1.8 MeV background
  - Precision measurement requires **O[<10 dru]** backgrounds, **O[<10 eV]** thresholds, and **kg scale**
- Detection of $\bar{\nu}_e$ from ^{238}U n-capture chain may be possible
- **Reactor bump detection beyond upcoming experiments**
  - **Zn/Ge** are best due to narrow bump

CEvNS is a powerful complementary tool to measure reactor neutrino fluxes and investigate tensions between IBD data and predictions

[Preliminary Results: Publication in Progress]

References:

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