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Engineering

Measuring the Antineutrino Spectrum Below 1.8 MeV

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Outline

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Potential applications in nuclear engineering

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Coherent elastic neutrino-nucleus scatters

Semiconductor detectors with Transition Edge Sensors

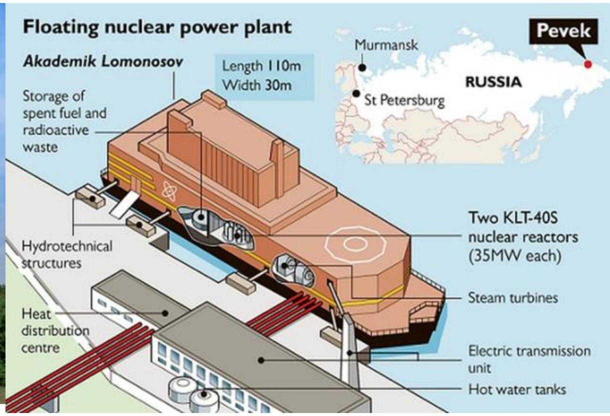
Antineutrino spectrum calculation for NE&SC

Cross-section determination

Final reaction rates in the detector

Current measurement setup

Future plans



Antineutrino Production

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- Antineutrinos are produced in the beta decay process
- Neutron rich fission products beta decay and release antineutrinos (~nearly 6 per fission event)
- Antineutrinos amount to ~5% of the released energy
- Detected for the first time at a nuclear reactor

$$n^0 \to p^+ + e^- + \bar{v}_e$$

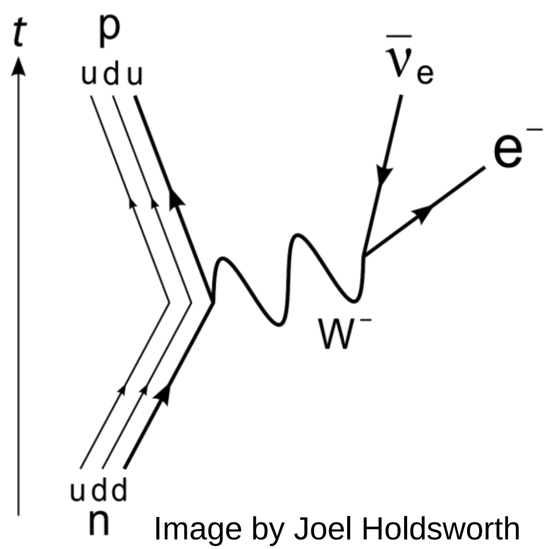

Image by Joel Holdsworth

Nucleus	E_{Th}	$\langle E_\nu \rangle$	$\langle N_\nu \rangle$	f_i/F
^{235}U	201.92 ± 0.46	9.07 ± 0.32	6.14	0.967
^{238}U	205.52 ± 0.96	11.00 ± 0.80	7.08	0.013
^{239}Pu	209.99 ± 0.60	7.22 ± 0.27	5.58	0.020
^{241}Pu	213.60 ± 0.65	8.71 ± 0.30	6.42	< 0.001
$^{238}\mathrm{U} \to {}^{239}\mathrm{Pu}$	1.95	1.2	2.0	0.16

PHYSICAL REVIEW D 93, 013015 (2016)

Potential applications of antineutrinos

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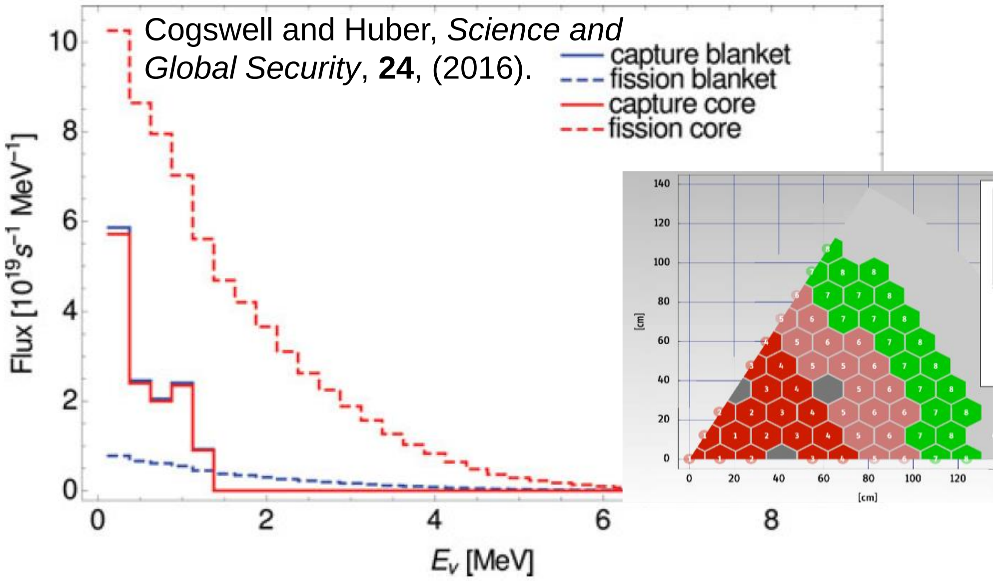
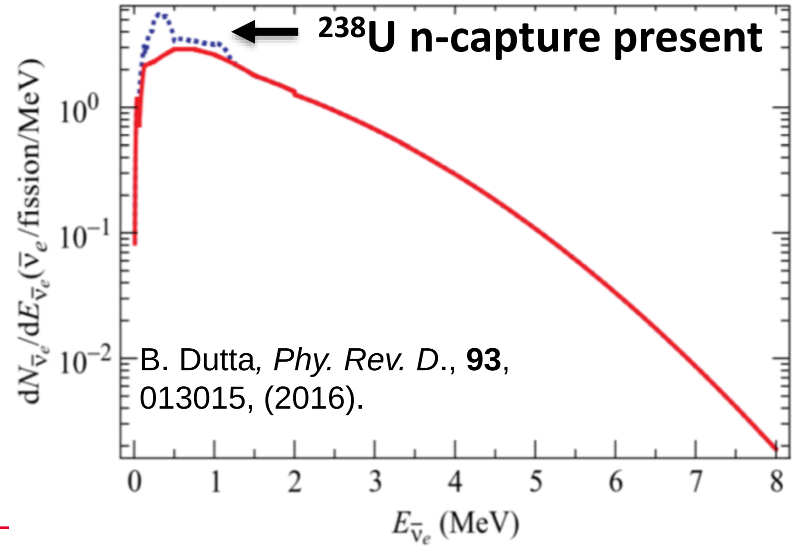
- Nuclear and particle physics, astrophysics, geothermal physics
- Reactor monitoring for total power, isotopics, burnup
  - Provide a way to calibrate ex-core detectors;
  - Measure power spikes and scram within a few seconds;
  - Detect presence of covert reactors or used nuclear fuel storage;
  - Measure U/Pu ratio;
  - Measure age of fuel, especially used nuclear fuel;
  - Determine reactor burning or breeding (antineutrino from capture different);
  - Advance fuels: tag and track may not work as well;
  - Post accident monitoring;





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Current Measurement Methods

- Traditional method uses inverse-beta-decay (IBD) to measure antineutrinos:

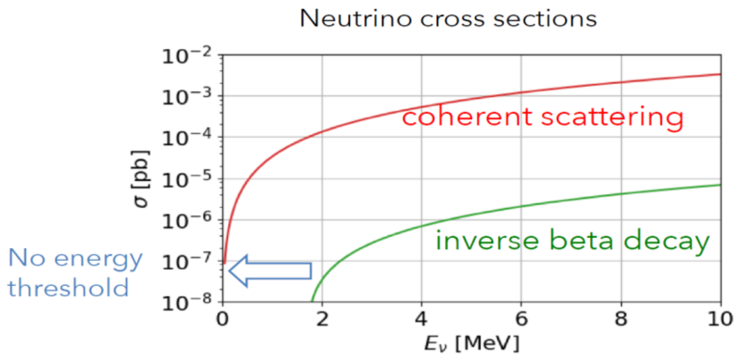
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

  - Cross-section of interaction (~10^{-42} barns), size tons-kilotons
  - Threshold of interaction 1.806 MeV
  - High maintenance, require photomultiplier tubes

- Necessitate the following characteristics:
  - NEED 1: An efficient detector providing high signal to noise quickly
  - NEED 2: Can provide detailed spectrum information
  - NEED 3: Ease of operation: low cost, low maintenance, portable

- ALTERNATIVE: coherent elastic neutrino-nucleus scatter (CNS)

Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), the University of Tokyo, Physics Today, 2018. 1-km underground, 50 kT of water



R. Strauss *Magnificent CEvNS, 2-3 November 2018 Chicago, IL* (2018).

Coherent elastic neutrino-nucleus scatter (CNS)

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- A mechanism for the antineutrino to scatter of a nucleus, the electrons, or the nucleons
- Postulated and formulated in 1974 by Freedman

$$\frac{d\sigma_{CNS}}{dT_R} = \frac{G_F^2 M}{2\pi}\left[(q_\nu + q_A)^2 + (q_\nu - q_A)^2 + \left(1 - \frac{T_R}{E_\nu}\right)^2 - (q_\nu^2 - q_A^2)\frac{MT_R}{E_\nu^2}\right]$$

σ_{CNS} is the coherent neutrino scattering cross-section
G_F is the Fermi coupling constant
q_V *and* q_A vector and axial charges
N is the number of neutrons

T_R is the recoiled nucleus' kinetic energy
M is the mass of the detector nucleus
E_ν is the energy of the anti/neutrino
Z is the atomic number

- First measured by the COHERENT group in 2017
  - Measurements performed for high energy neutrinos (not completely coherent w.r.t. nucleus)
- At lower energies as in from nuclear reactor (<10 MeV)

Ge/Si detectors with Transition Edge Sensors by Mahapatra Group, Texas A&M

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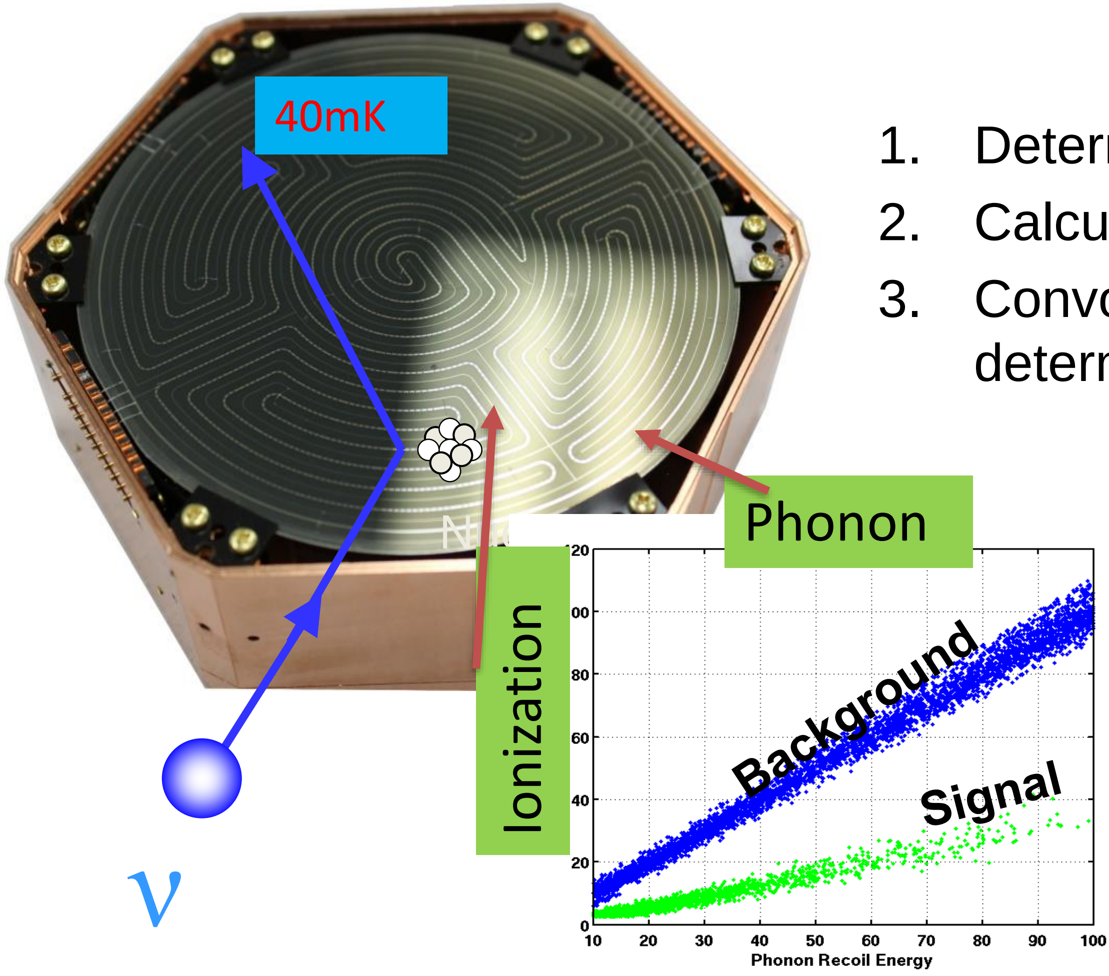
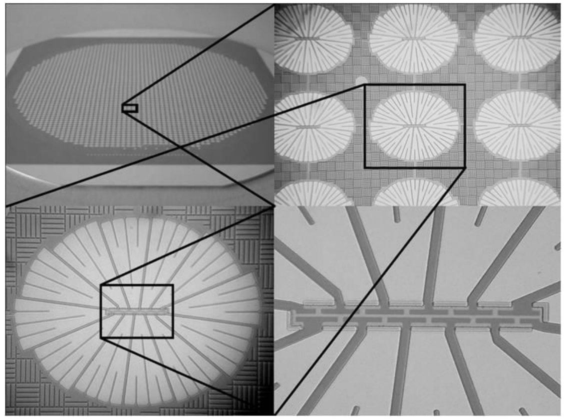
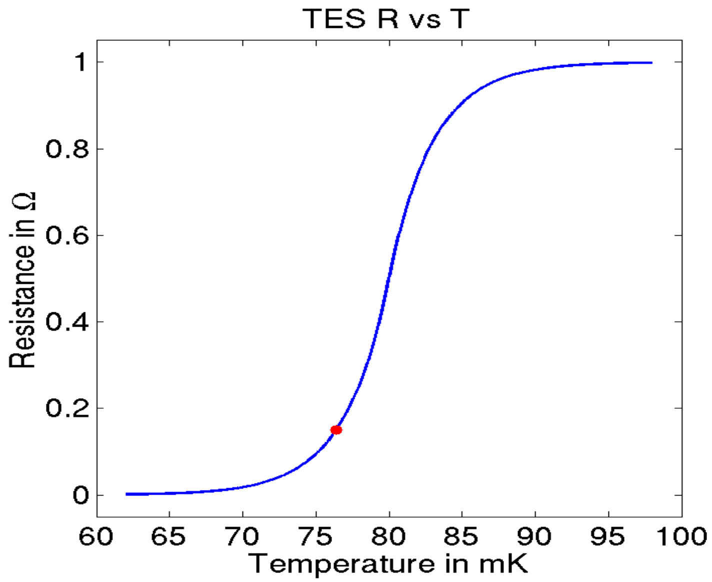


General Procedure

1. Determine the antineutrino flux for reactor of interest
2. Calculate the CNS cross-sections for the detectors of choice
3. Convolve the antineutrino flux and CNS cross-sections to determine reaction rates





Calculation of the antineutrino spectrum

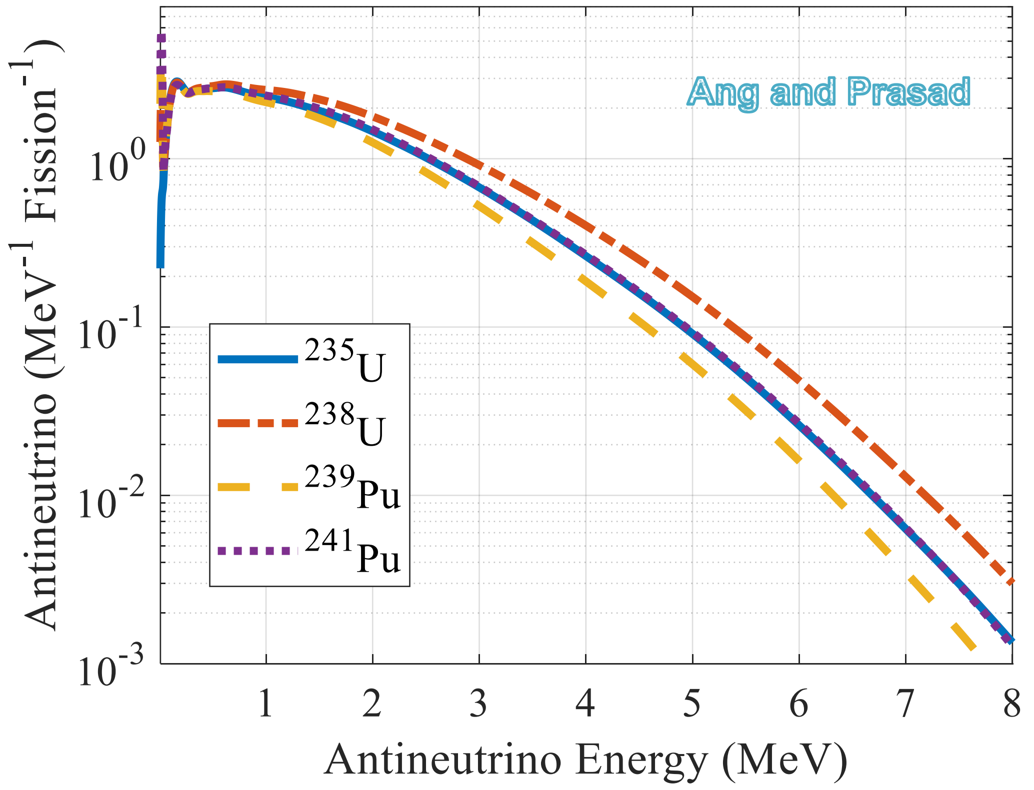
1. Determine the antineutrino flux for reactor of interest (10 m from 1-MW NE&SC core-Texas A&M)
   - Ab-initio or the summation method, for a given fissile isotope determine all fission products that decay by β-decay, obtain the β-decay spectrum, sum-up and subtract from β_{max} energy (our choice)

$$\rho(E_\nu) = \sum CY_i \sum BR_i P_i(E_\nu)$$

i is fission product index, CY_i is cumulative yield if isotope, BR_i is branching ratio, $P(E_{\nu i})$ is the neutrino energy distribution

$$P_i(E_\nu)dE_\nu = F(Z, E_\nu)\left[(E_{\beta\max} - E_\nu)^2 - m_0^2c^4\right]^{\frac{1}{2}} \times \frac{E_\nu^2(E_{\beta\max}-E_\nu)dE_\nu}{F_i} \times F_a(E_\nu)$$

$F(Z, E_\nu)$ is the fermi function, $F_a(E_\nu)$ is a correction factor for spin-parity-forbidden/allowed states



W. E. Ang, S. Prasad, R. Mahapatra, Proceedings of *IEEE-NSS-MIC* (2020)

- 545 fission products for ^{235}U
- 586 fission products for ^{238}U
- 568 fission products for ^{239}Pu
- 605 fission products for ^{241}Pu

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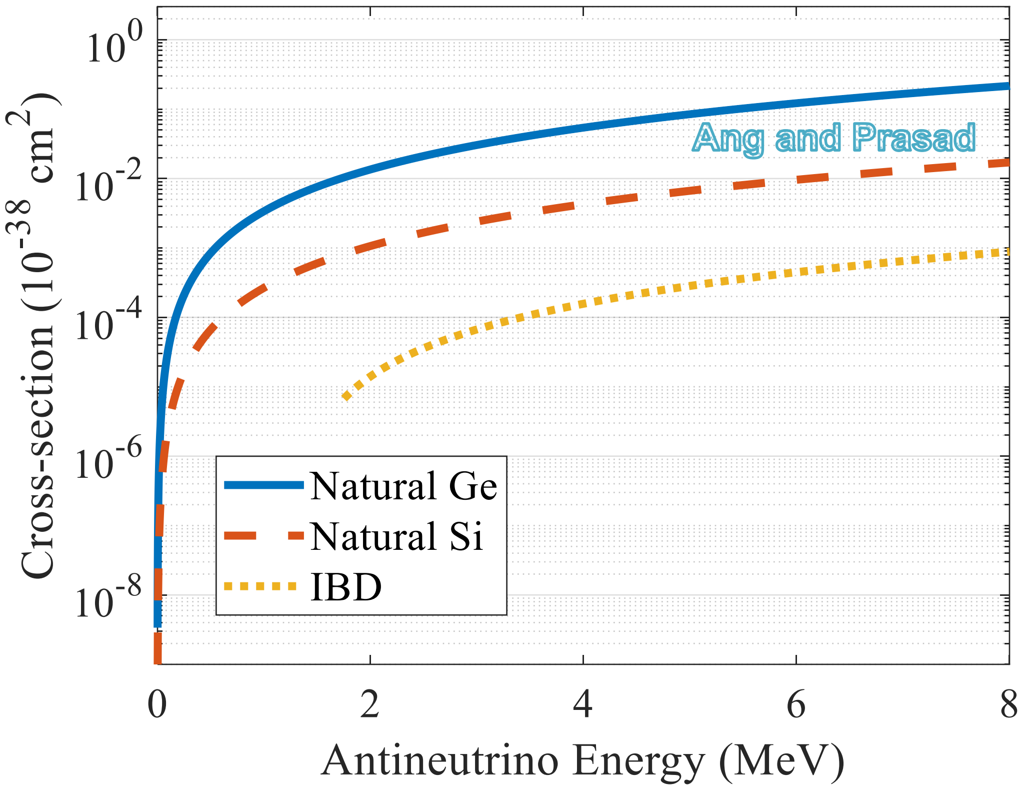
Calculation of the Detection Cross-section

- The differential cross-section as a function of nucleus recoil energy is integrated up to

$$T_R^{Max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

- The resulting cross-section for Ge and Si indicate germanium is more efficient over all energies
- Detector threshold of 20 eV nuclear recoil

Detector Technology	Flux-weighted cross-section
Germanium CNS	4×10^{-4} pb
Silicon CNS	3.2×10^{-5} pb
IBD	1.88×10^{-6} pb

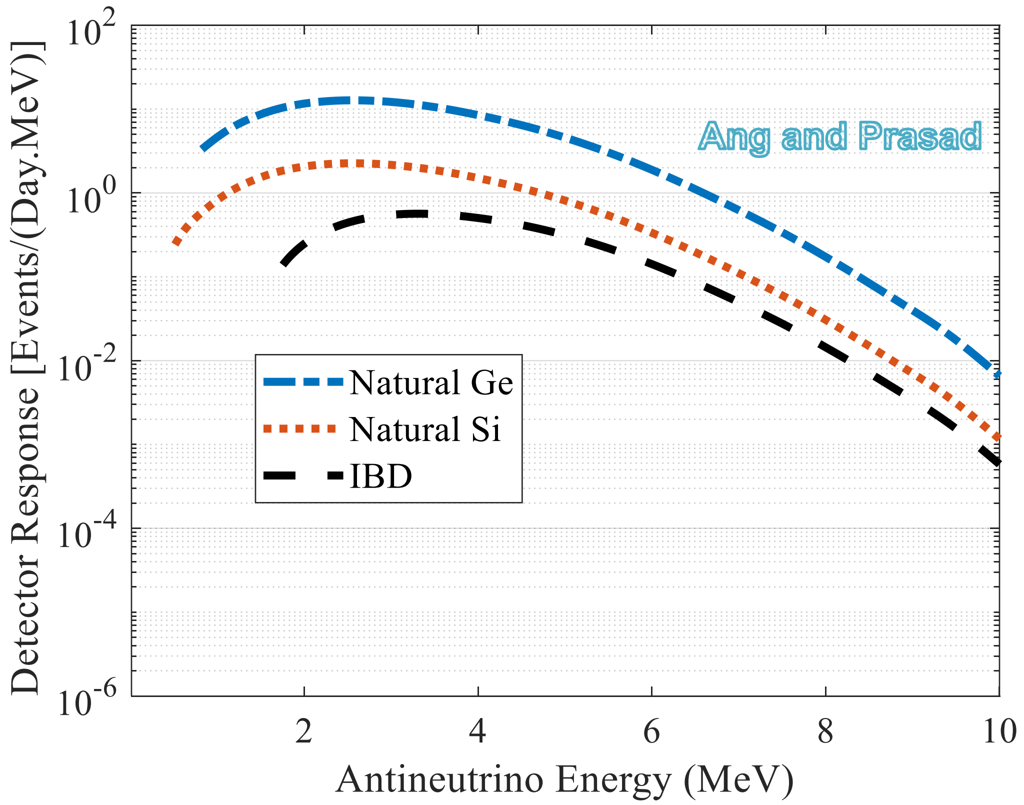


W. E. Ang, S. Prasad, R. Mahapatra, *Nucl. Inst. & Meth. A* (submitted)

Reaction Rates in the Detector

$$R(E_\nu) = N\sigma_{CNS}(E_\nu)\phi(E_\nu)$$

- At 20 eV nuclear recoil, minimum detectable neutrino energy on Si ~0.5 MeV, on Ge ~0.8 MeV (100 kg detector at 10 m)
  - ~43.4 events/day in Ge and ~7.8-events/day in Si
  - Antineutrinos missed nearly 32% in Ge and 19% in Si
- At 100 eV nuclear recoil, minimum detectable neutrino energy on silicon ~1.14 MeV, on germanium ~1.84 MeV
- The current inverse-beta-decay (IBD) threshold at ~1.8 MeV
  - ~2.1 events/day with water based and ~1.8 events/day with organic scintillation based IBD detectors
  - Antineutrinos missed nearly 50%



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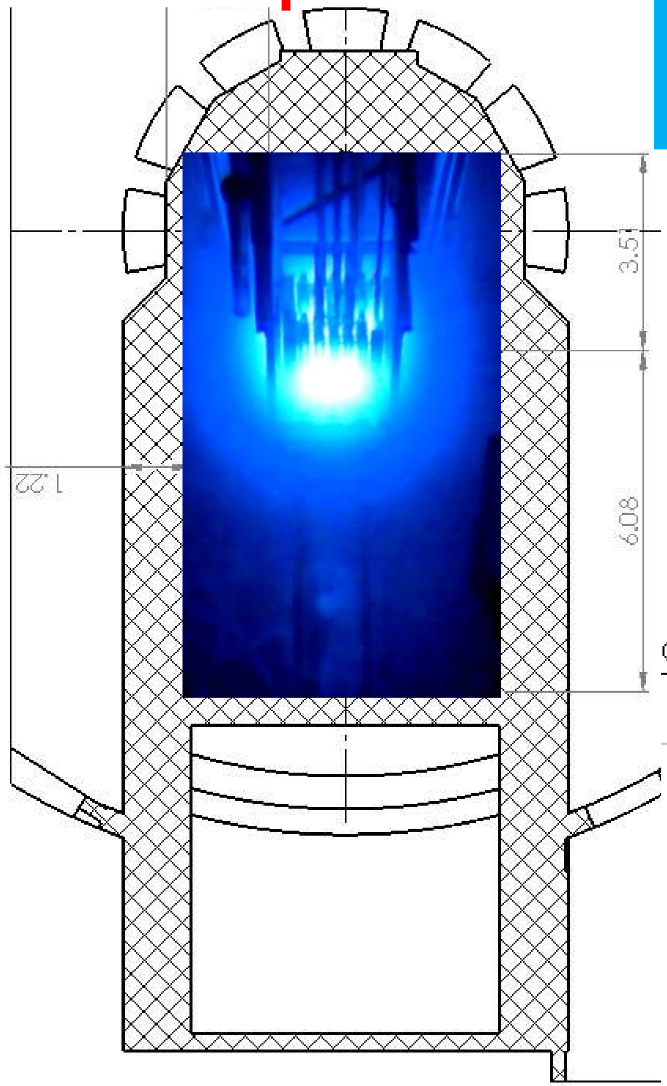
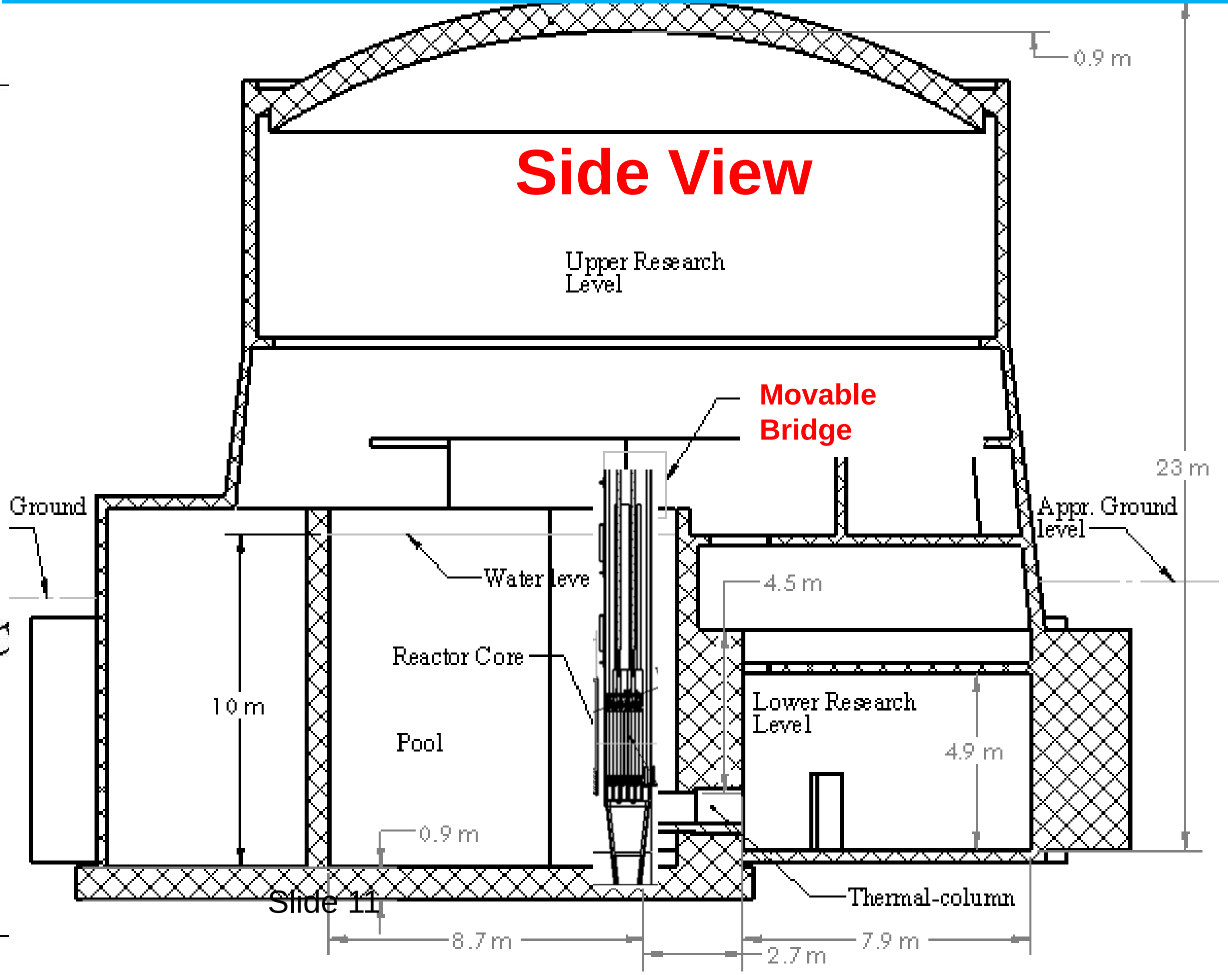
MINER experiments plan

Top View



1. 2-10 m proximity to core (rate enhancement)
2. Moveable Core tests short baseline oscillation
3. 4 kg (max=30) detector payload



Summary and Future Plans

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- Shown detector’s response as a function antineutrino energies for CNS semiconductors (below 1.8 MeV)
  - Ge more efficient than Si detectors
  - Si provides lower threshold for detection
  - Both semiconductors can be developed to provide more efficient and smaller detectors (possibly cheaper)
- Formulate detector response beyond reaction rates
- Perform analysis for different cases: fuel cycles, burnup history, power levels
- Perform spectrum reconstruction of antineutrino energies from the detector response function above

MIνER Compact Installation with Bluefors closed-cycle fridge at Texas A&M

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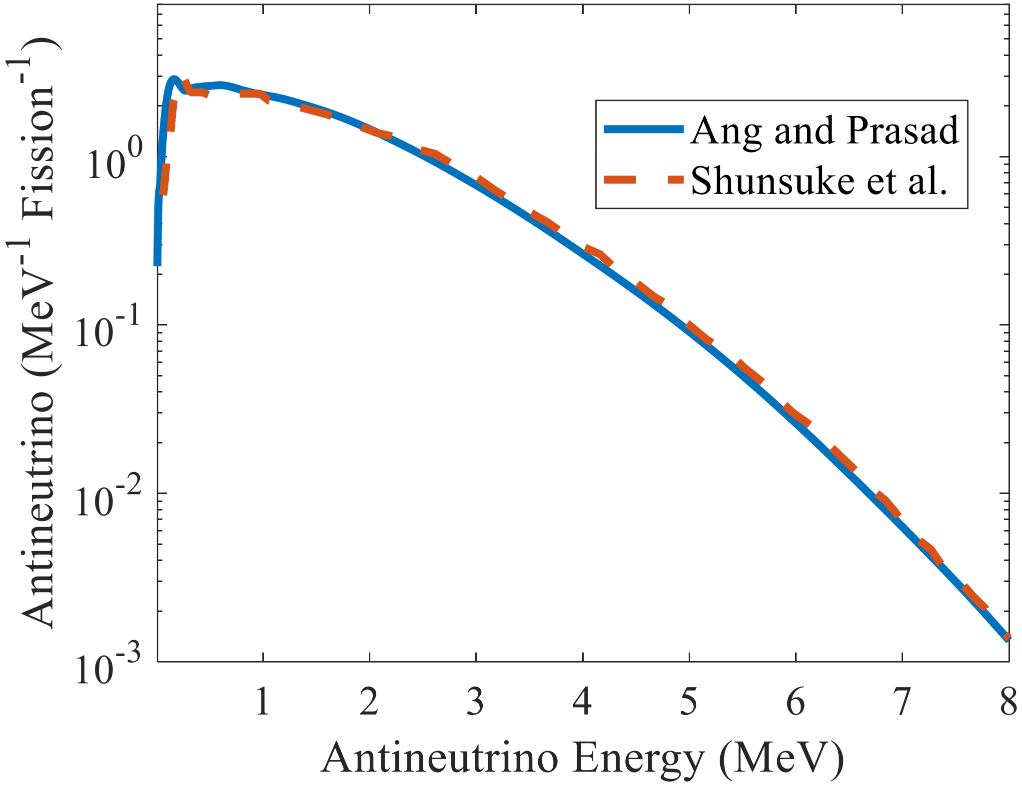
Additional Remarks



$$F_a(E_v) = C(1 - E_v/E_{max})^n$$

$$F(Z,W) \approx a\frac{W}{p} + \left[\frac{c}{1+(d/p^2)}\right]$$

where $a = 2\pi\alpha Z, C = b - a, b = a/(1 - e^{-a})$, and $d = \left(\frac{1}{2}\right)(b - 1)$

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