MIT Nuclear Science and Engineering

LNS
Laboratory for Nuclear Science

CEvNS in Superconductors and its Applications for Finding Trafficked Radioactive Materials

Brianna Noelani Ryan, Joseph Formaggio,
& Michael Short

Nuclear non-proliferation entails the safeguards of many types of nuclear technology.

Nuclear

Non-Proliferation

- **Radioactive Materials**
- Nuclear Weapons
- Fission Reactors
- Spent Nuclear Fuel
- Fusion Reactors

The top five most smuggled isotopes.

Isotope	Cs-137	Am-241	Cd-109	Ir-192	Co-57
% of Incidents	56.8%	48.4%	13.2%	6.1%	5.8%
Decay Type	Beta	Alpha	EC	Beta, EC	EC

*Statistics Obtained from the CNS Global Incidents and Trafficking Database
** Cs-137 stated as the most commonly trafficked isotope in the US by the Department of Defense

Goal: Assess whether it is theoretically possible to detect any of these trafficked radioactive materials using CEvNS

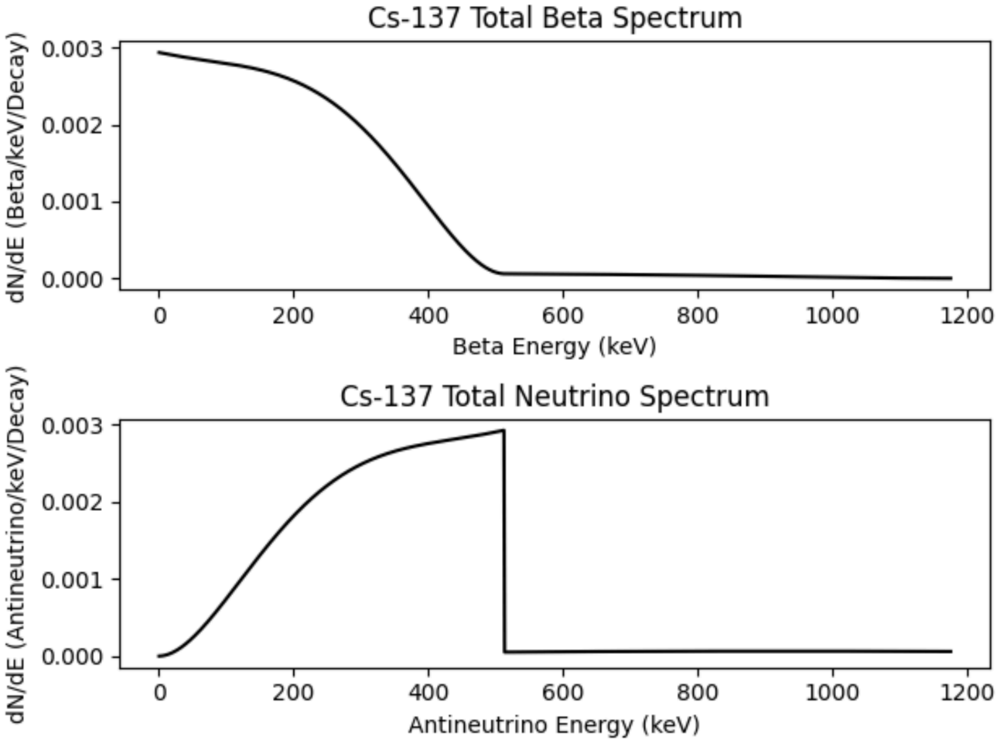
To do this we must…

1. Generate the Neutrino Spectra
2. Compute the CEvNS Cross Section
3. Calculate the CEvNS Reaction Rate
4. Determine Minimum Detector Size

Step 1: Generate Neutrino Spectra

Case #1: Cs-137

$${}^{137}_{55}Cs - >^{137}_{56} Ba + \beta^- + \bar{\nu}_e$$



Step 2: Compute the CEvNS Cross Section

The CEvNS cross-section can be derived directly from the Standard Model.

$$\sigma(E_\nu) = \frac{G_F^2}{4\pi}\overbrace{E_\nu^2}^{\text{Neutrino Energy}}\underbrace{Q_W^2}_{\text{Weak Nuclear Charge}}(1-\frac{\overbrace{T_0}^{\text{Recoil Threshold}}}{\underbrace{T_{max}}_{\text{Maximum Recoil Energy}}})^2$$

Why use superconductors?

1. The Ricochet Collaboration is working towards a CEvNS superconducting detector to measure reactor neutrinos
2. Theoretically, one could achieve very low recoil thresholds
3. Superconductors would have much less thermal noise

The recoil threshold can theoretically get as low as the gap energy.

Material	**Mass**	**Critical Temperature**	**Gap Energy**	**Min Neutrino Energy**
Aluminum	26.982 amu	1.19 K	0.338 meV	2.062 keV
Zinc	65.397 amu	0.875 K	0.241 meV	2.711 keV
Tin	118.699 amu	3.722 K	1.122 meV	7.877 keV

The recoil threshold can theoretically get as low as the gap energy.

Material	Mass	Critical Temperature	Gap Energy	Min Neutrino Energy
Aluminum	26.982 amu	1.19 K	0.338 meV	2.062 keV
Zinc	65.397 amu	0.875 K	0.241 meV	2.711 keV
Tin	118.699 amu	3.722 K	1.122 meV	7.877 keV

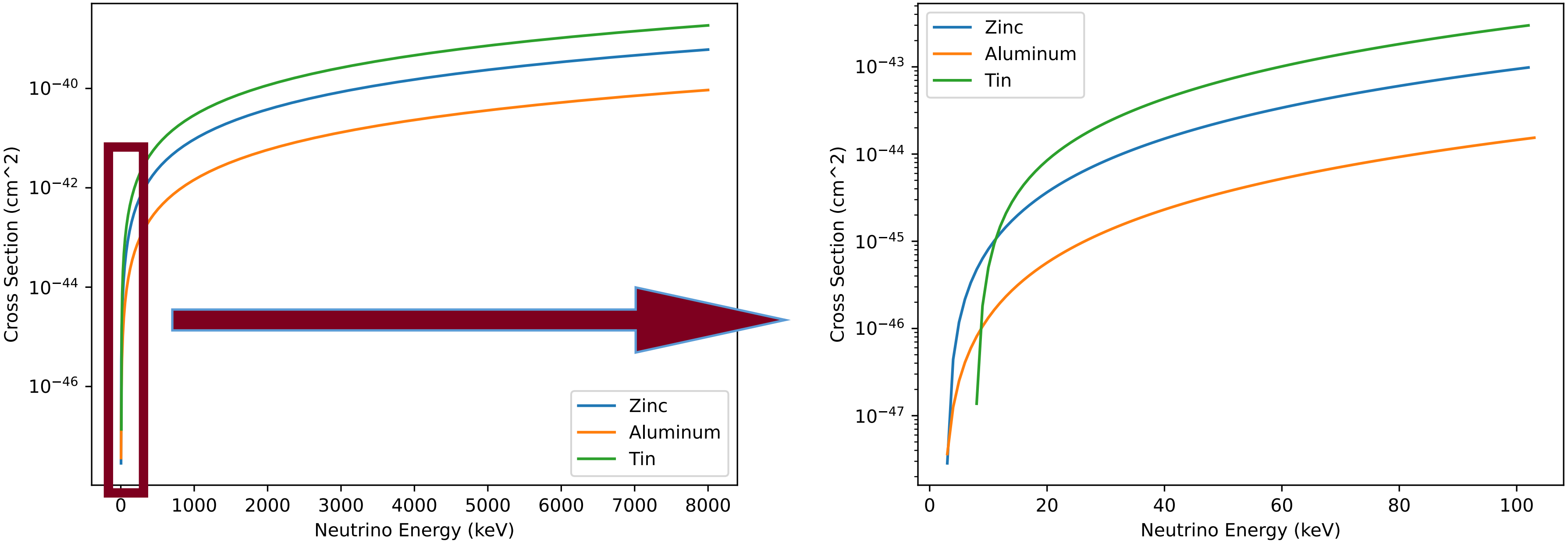
$$2\Delta = 3.2k_BT_c$$

The recoil threshold can theoretically get as low as the gap energy.

Material	Mass	Critical Temperature	Gap Energy	Min Neutrino Energy
Aluminum	26.982 amu	1.19 K	0.338 meV	2.062 keV
Zinc	65.397 amu	0.875 K	0.241 meV	2.711 keV
Tin	118.699 amu	3.722 K	1.122 meV	7.877 keV

$$E_{\nu,min} = \frac{1}{2}T_0 + \frac{1}{2}\sqrt{T_0^2 + 2T_0M}$$

Despite it’s high recoil threshold, tin is typically the best detection material.

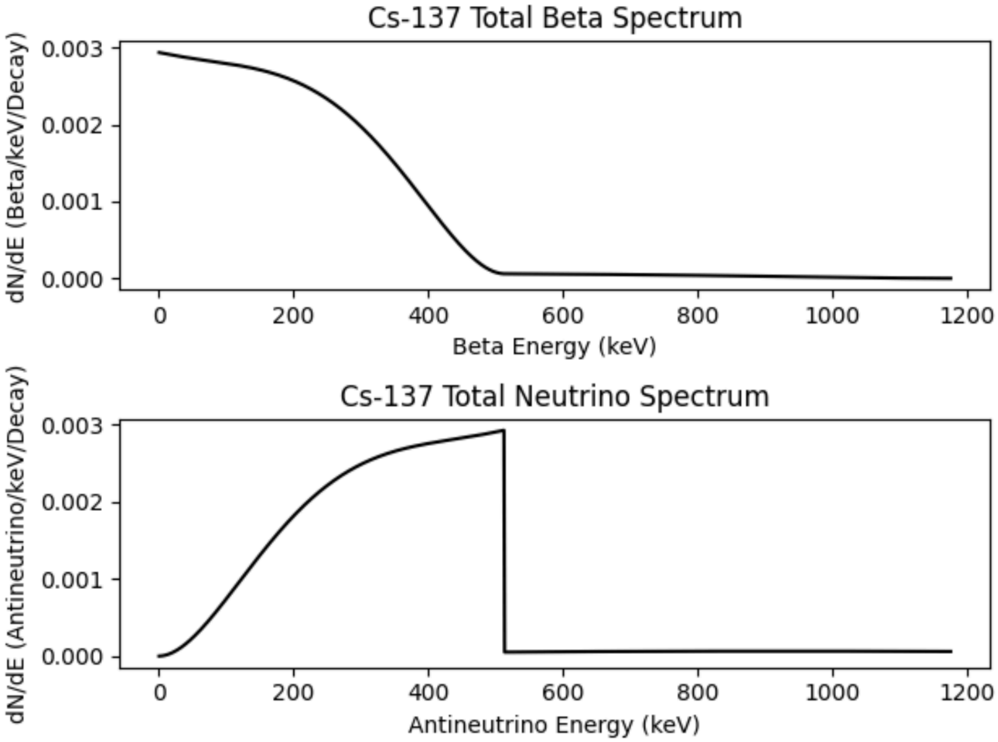


Case #1: Cs-137

$$^{137}_{55}Cs - >^{137}_{56} Ba + \beta^- + \bar{\nu}_e$$

Detector Material = Tin

$$< \sigma > = 4.303 \times 10^{-42}\ \text{cm}^2$$



Cs-137 Total Beta Spectrum

Cs-137 Total Neutrino Spectrum

Step 3: Calculate the CEvNS Reaction Rate

Approximating the source as a point source, the reaction rate is…

$$S(E_\nu) = \overbrace{N_t}^{\text{\# of Detectors}} \underbrace{R}_{\text{Source Activity}} \overbrace{\sigma(E_\nu) f(E_\nu, T_0)}^{\text{CEvNS Cross Section}} \frac{N_A}{A} \underbrace{M_t}_{\text{Mass of Detector}} \frac{\overbrace{\xcancel{P(E_\nu, \bar{r}_i)}}^{\text{Oscillation Probability}}}{\underbrace{4\pi \bar{r}_i{}^2}_{\text{Source to Detector Distance}}}$$

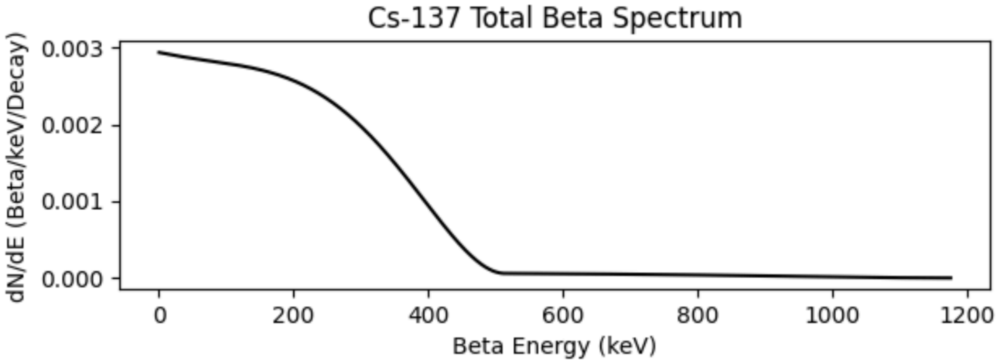
Case #1: Cs-137

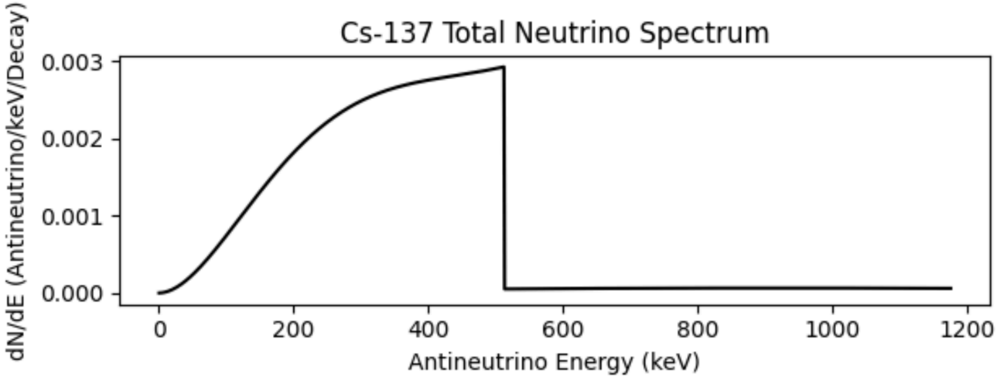
$$^{137}_{55}Cs -> ^{137}_{56} Ba + \beta^- + \bar{\nu}_e$$

Detector Material = Tin

$< \sigma > = 4.303 \times 10^{-42}$ cm^2

Rx Rate = 5.685×10^{-7} events per kg-Ci-day





Step 4: Determine Minimum Detector Size

Statistical Question: How to be 95% confident that there is **not** a neutrino emitting source present

Radioactive decay is a Poisson process.

$$f(\underset{\text{\# of Counts Observed}}{k};\ \overset{\text{\# of Counts Expected}}{\lambda}) = \frac{\lambda^k e^{-\lambda}}{k!}$$

PDG Limit: $\lambda \geq 3.09$

Combing step 3 and step 4, we get an equation to solve for the minimum mass of the detector.

$$\overbrace{M_d = M_t N_t t}^{\textbf{Mass of Detector}} = \frac{4\pi\lambda A r_i^2}{\bar{\sigma} N_A}\frac{1}{\underbrace{R}_{\textbf{Source Activity}}}$$

Case #1: Cs-137

Ex 1: NIS 04/2012

Activity $= 1.607 \times 10^{15}$ Bq

@1 m $= 185$ ton-min

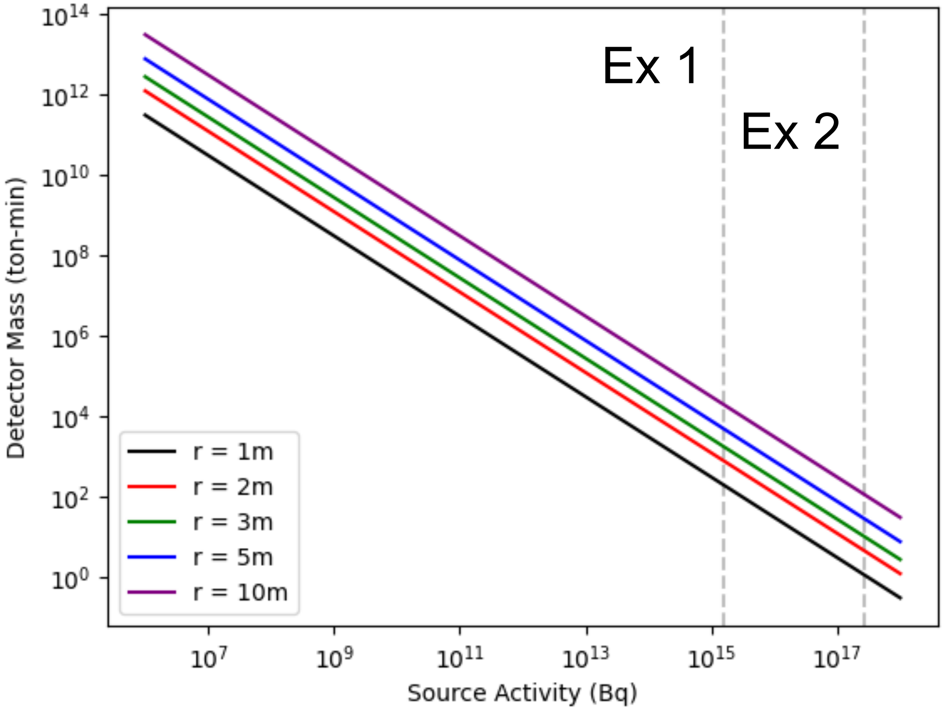
@5 m $= 4630$ ton-min

Ex 2: NIS 01/2005

Activity $= 2.667 \times 10^{17}$ Bq

@1 m $= 1.116$ ton-min

@5 m $= 28$ ton-min



The Other Cases

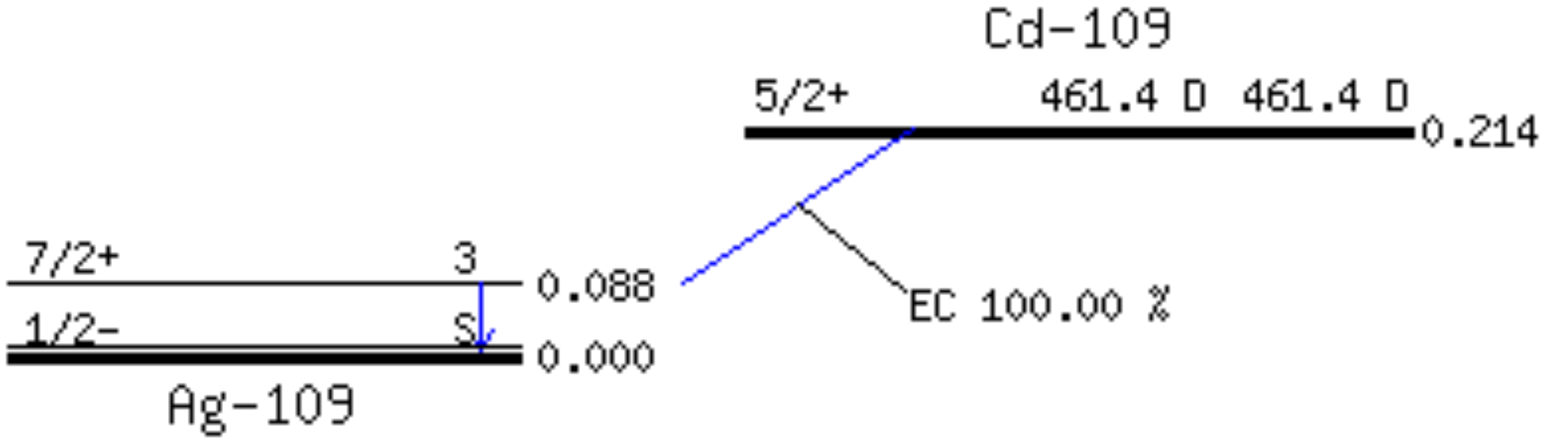
Case #2: Cd-109

$^{109}_{48}Cd -> ^{109}_{47}Ag + \nu_e$

$< \sigma > = 4.726 \times 10^{-43}$ cm^2

Detector Material = Tin

Rx Rate = 7.054×10^{-13} events per kg-Ci-day



Case #2: Cd-109

Ex 1: CNS 01/2013

Activity $= 1.240 \times 10^9$ Bq

@1 m $= 2.186 \times 10^9$ ton-min

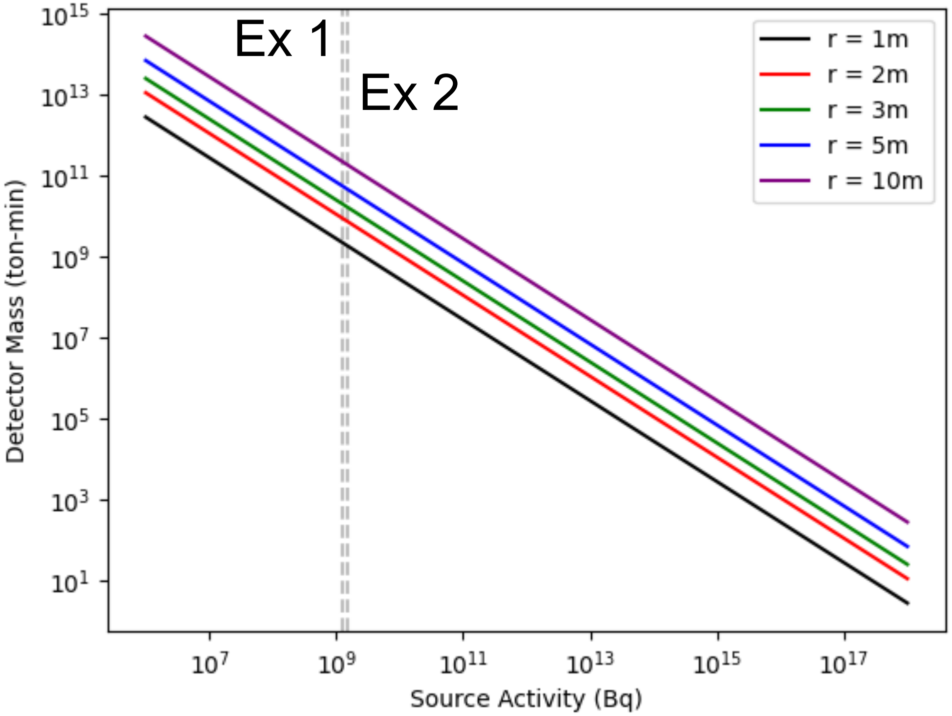
@5 m $= 5.464 \times 10^{10}$ ton-min

Ex 2: CNS 08/2018

Activity $= 1.480 \times 10^9$ Bq

@1 m $= 1.831 \times 10^9$ ton-min

@5 m $= 4.578 \times 10^{10}$ ton-min



Case #3: Ir-192

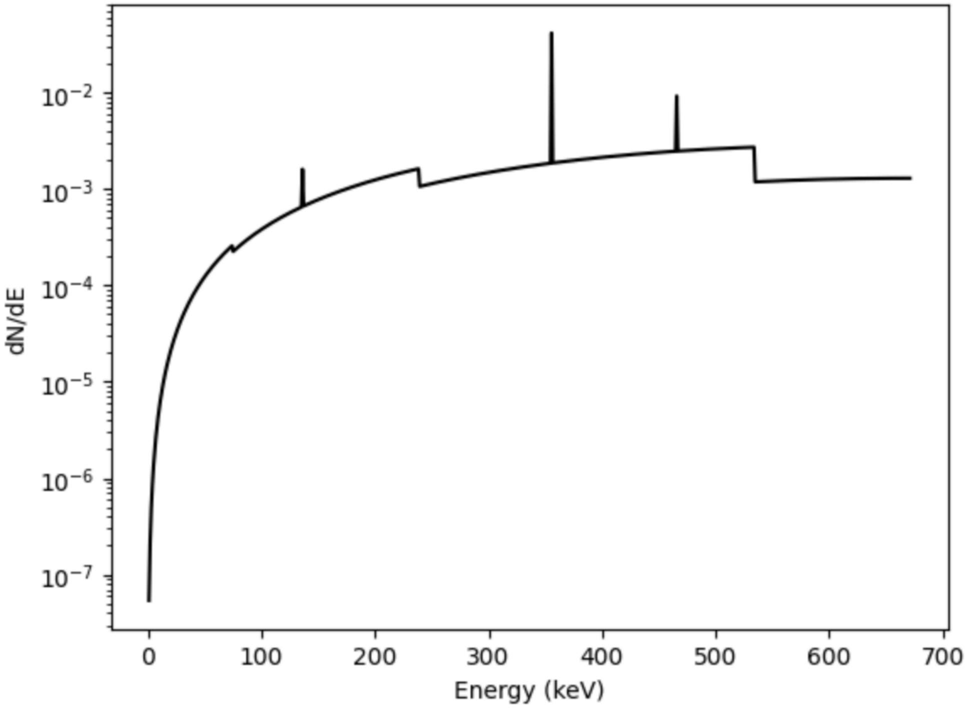
$$^{192}_{77}Cd->^{192}_{78}Ag+\beta^{-}+\bar{\nu}_e$$

$$^{192}_{77}Cd->^{192}_{76}Os+\nu_e$$

Detector Material = Tin

$< \sigma > = 5.340 \times 10^{-42}$ cm^2

Rx Rate $= 6.598 \times 10^{-7}$ events per kg-Ci-day



Case #3: Ir-192

Ex 1: CNS 09/2018

Activity $= 108$ Ci

@1 m $= 60021$ ton-min

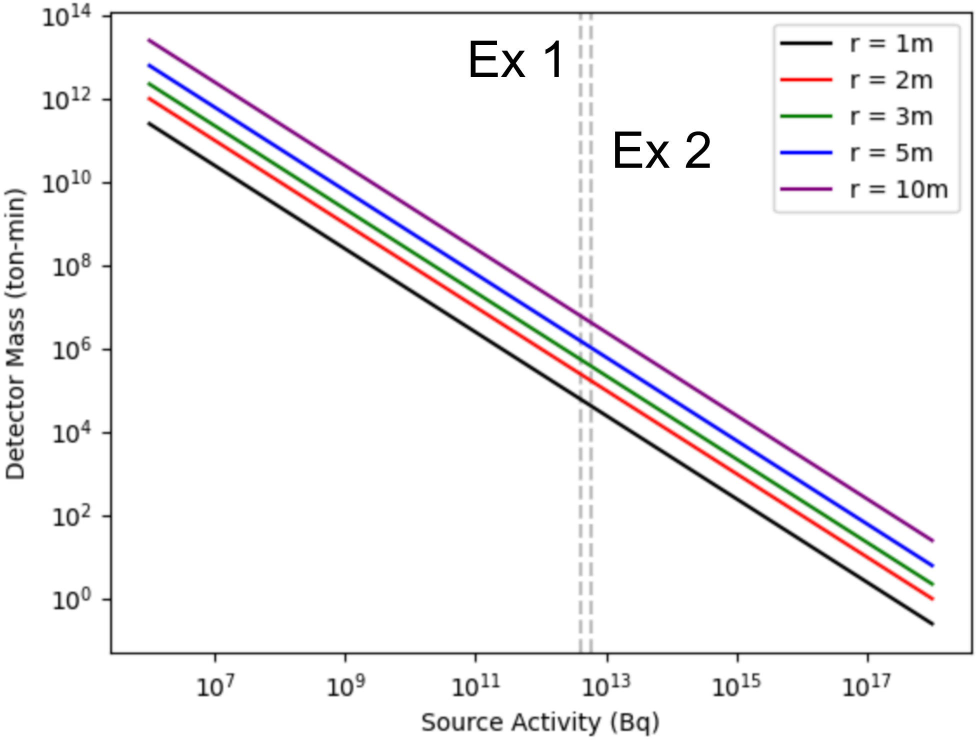
@5 m $= 1.501 \times 10^6$ ton-min

Ex 2: CNS 04/2019

Activity $= 159$ Ci

@1 m $= 40769$ ton-min

@5 m $= 1.019 \times 10^6$ ton-min



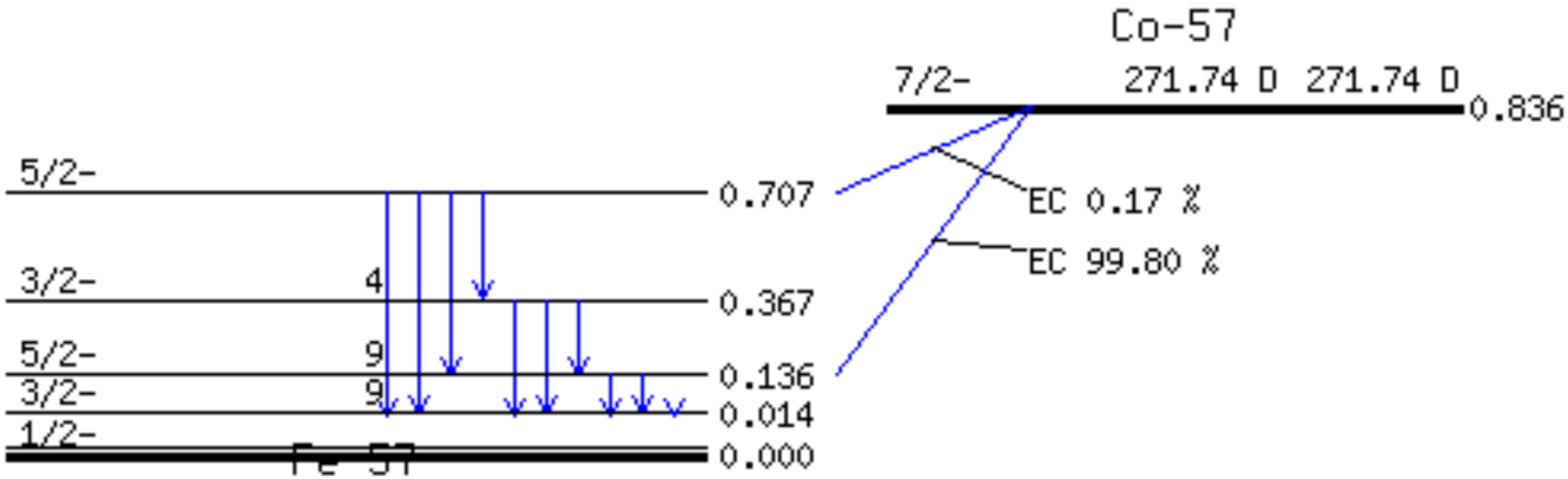
Case #4: Co-57

$^{57}_{27}Co - >^{57}_{26}Fe + \nu_e$

$< \sigma > = 1.420 \times 10^{-41}$ cm^2

Detector Material = Tin

Rx Rate = 2.120×10^{-11} events per kg-Ci-day



Case #4: Co-57

Ex 1: CNS 09/2022

Activity $= 3.48 \times 10^8$ Bq

@1 m $= 2.592 \times 10^8$ ton-min

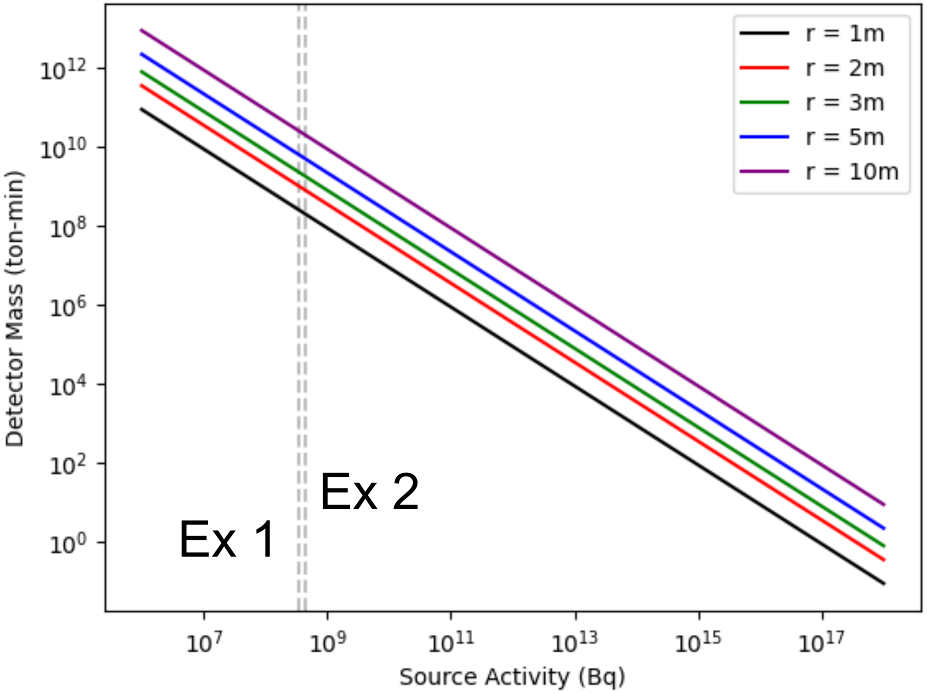
@5 m $= 6.480 \times 10^9$ ton-min

Ex 2: CNS 03/2015

Activity $= 4.44 \times 10^8$ Bq

@1 m $= 2.031 \times 10^8$ ton-min

@5 m $= 5.079 \times 10^9$ ton-min



Theoretical Conclusions:

In conclusion, CEvNS is only capable of detecting large amounts of **Cs-137** being smuggled.

How many events it could detect can be better established with a **more comprehensive trafficking event database**.

Where do we stand experimentally?

Current experimental limits are far from the theoretical “best case” scenario.

As approximate experimental parameters lets use…

- Detector Temperature: 20 mK (from Q-Array)
- Recoil Threshold: 35 eV (from CryoCube)
- Efficiency: 50% (approx based on CryoCube)

Background noise will be taken into consideration as Q-Array’s R&D progresses.

How does recoil threshold effect our detector?

Material	Theoretical Min Energy	Experimental Min Energy
Aluminum	2.062 keV	0.663 MeV
Zinc	2.711 keV	1.032 MeV
Tin	7.877 keV	1.391 MeV

While these are all less than the IBD threshold at ~1.8 MeV, they are too high for detecting most of our isotopes of interest.

How does efficiency effect the detector?

$$M_d = M_t N_t t = \frac{4\pi\lambda A r_i^2}{\bar{\sigma} N_A \underbrace{\epsilon}_{}} \frac{1}{R}$$

Detector Efficiency

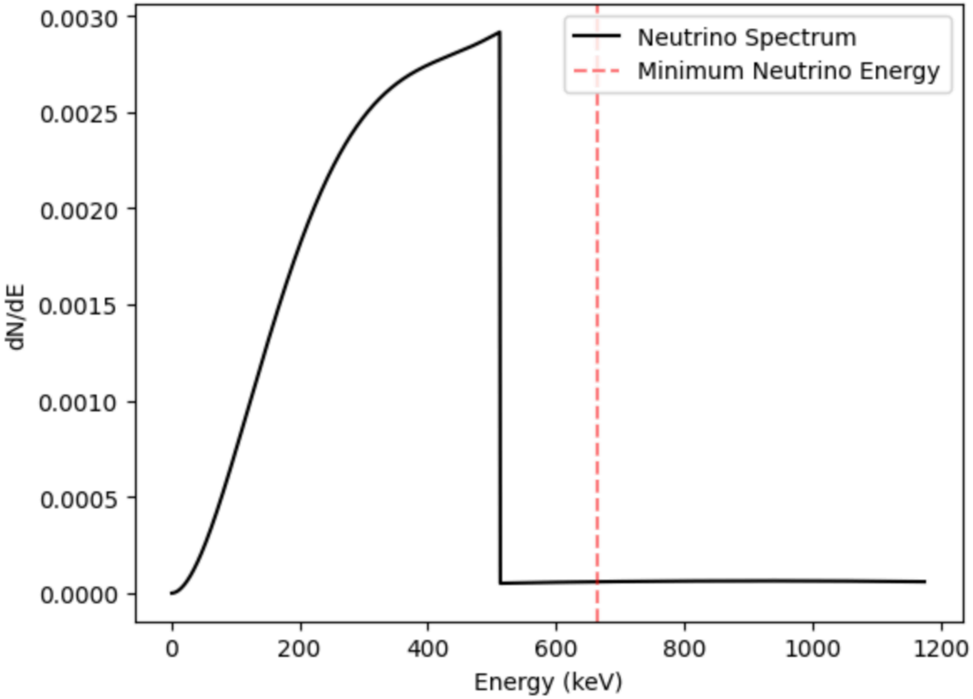
Case #5: Cs-137 in 2024

$$^{137}_{55}Cs -> ^{137}_{56}Ba + \beta^- + \bar{\nu}_e$$

Detector Material = Aluminum

$< \sigma > = 3.427 \times 10^{-43}$ cm^2

Rx Rate = 2.557×10^{-7} events per kg-Ci-day



Case #5: Cs-137 in 2024

Ex 1: NIS 04/2012

Activity $= 1.607 \times 10^{15}$ Bq

@1 m $= 1.461 \times 10^{5}$ ton-min

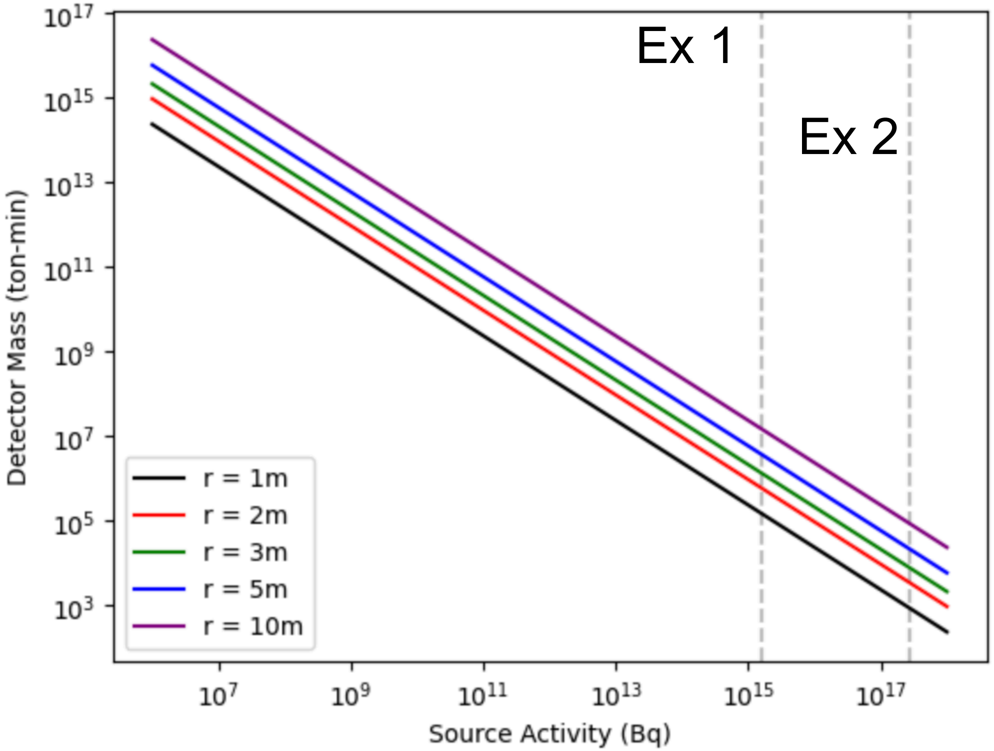
@5 m $= 3.651 \times 10^{6}$ ton-min

Ex 2: NIS 01/2005

Activity $= 2.667 \times 10^{17}$ Bq

@1 m $= 880$ ton-min

@5 m $= 22001$ ton-min



Conclusions:

- Off the five most trafficked radioactive isotopes, four emit neutrinos: **Cs-137, Cd-109, Ir-192, & Co-57**.
- In theoretical “best detection” scenarios, **only large Cs-137 events** would be reasonably detectable.
- Applying some current experimental limitations, **extremely large Cs-137 trafficking events could still be detected with very large detectors.**

Future Work

- These results were formed with the very limited CNS database. A **more comprehensive trafficking database** would provide better insight.
- **Background noise** needs to be incorporated into non-theoretical results. The goal is to use Ricochet's q-array background noise models after R&D is complete.
- The main goal of this work was to form an **analysis method for quantifying minimum theoretical detector size.** With that established, this work can be applied to more pressing safeguard issues.

Acknowledgements

Special thanks to my co-authors and advisors, Professor Joseph Formaggio and Professor Mike Short.

Thanks to Dr. Doug Pinckney for all of his support.

Thanks to MIT and the Lemensons for sponsoring my research.

Thank you for listening!

I am happy to answer any questions.

Back Up Slides

To determine the neutrino spectrum from β decay, we use a fermi approximation.

$$N_\beta(W_e) = \overset{\text{Normalization Constant}}{\overline{K}}\,\underset{\text{Beta Momentum \& Energy}}{\underline{p_e W_e}}\,\overset{\text{Neutrino Momentum \& Energy}}{\overline{p_\nu W_\nu}}\,\underset{\text{Fermi Function}}{\underline{F(Z, W_e)}}\,\overset{\text{Theoretical Shape Factor}}{\overline{C(W_e)}}$$

How does detector temperature effect our detector?

Having detectors hotter than 0K effects our gap energy.

At 20 mK, there is almost no change to the gap energy!

Heating up the detector does introduce thermal noise.