Inverse beta decay and coherent elastic neutrino nucleus scattering – a comparison

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ABSTRACT

Many neutrino experiments involving low-energy neutrinos rely on inverse beta decay (IBD), including those studying neutrino oscillations at nuclear reactors, and for applications in reactor monitoring and the detection of neutrinos emitted from spent nuclear fuel. IBD reactions can occur only for electron antineutrinos with energy above a threshold of 1.806 MeV. Below this threshold, the signature of neutrinos is accessible via coherent elastic neutrino-nucleus scattering (CEνNS), a threshold-less reaction. CEνNS was observed for the first time in 2017 at 6.7σ confidence level after forty years of experimentation, albeit with neutrinos of about 10 times larger energy than those from reactors. Here we assume also that neutrinos from reactors and other MeV-sources eventually will be detected using CEνNS. In this paper, we use neutrino fluxes measured from reactors and their cross sections to compute the energy spectra of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, and determine and compare neutrino detection event counts using either IBD or CEνNS. This characterization will inform future detector choices and is directly applicable to various neutrino sources, including reactor neutrinos, spent fuel neutrinos, and geoneutrinos. The result is potentially useful in monitoring spent nuclear fuel and reactors, in support of nuclear nonproliferation safeguards objectives.

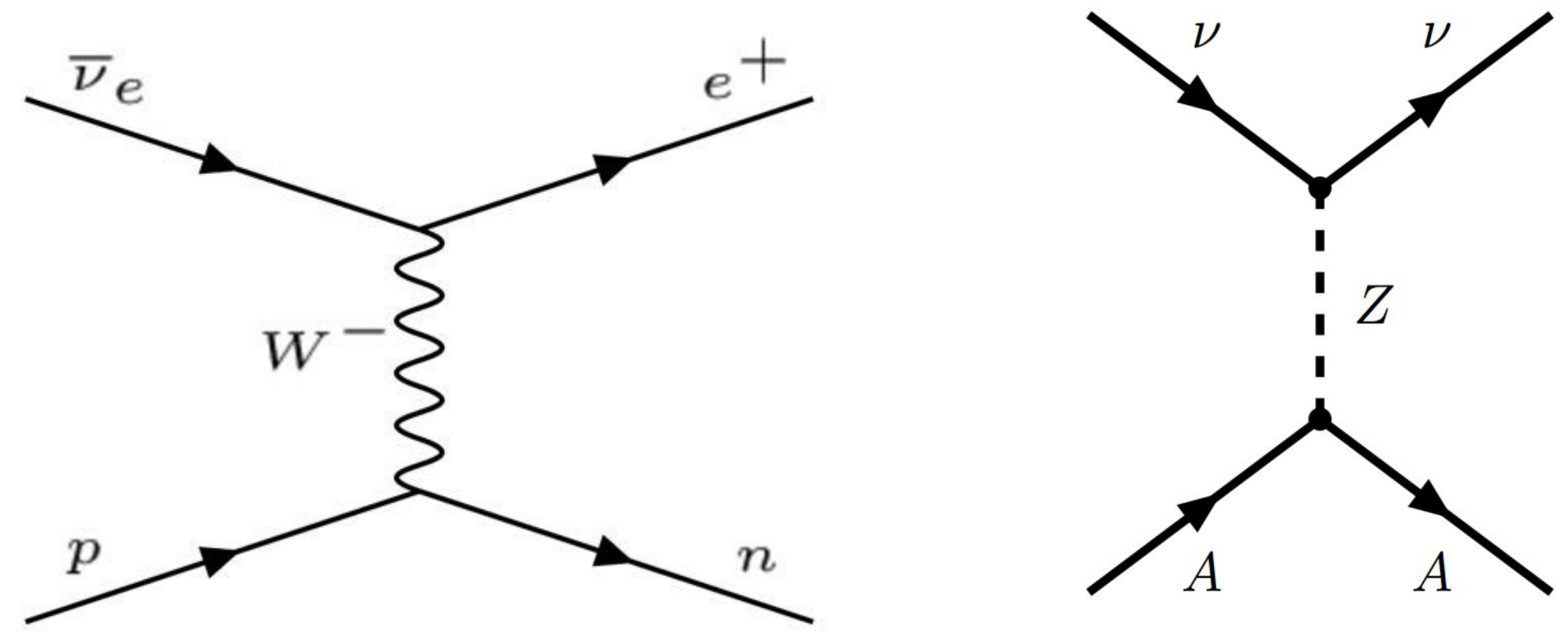

Fig. 1.1-1.2 (left, right)
Feynman diagrams of IBD and CEνNS, respectively

INTRODUCTION

Inverse beta decay (IBD) is an important process commonly used to study lower-energy neutrinos of less than 60 MeV and is used in most reactor experiments. Coherent elastic neutrino-nucleus scattering (CEνNS) is a promising detection method for low-energy neutrinos due to its cross section's N^2 dependence, where N is the number of nucleons in the target mass. The result is potentially much smaller detectors that observe far more neutrinos. Despite its high cross section, CEνNS evaded detection for decades because of the difficulty in detecting very low nuclear recoil energies. Physicists can use IBD and potentially use CEνNS to monitor nuclear reactors for weapons-grade material as well as managing spent nuclear fuel. These detection methods can also be used to study geoneutrinos and study neutrino properties.

Isotope	^{239}Pu	^{241}Pu	^{235}U	^{238}U
Events	3000	4160	4360	6580

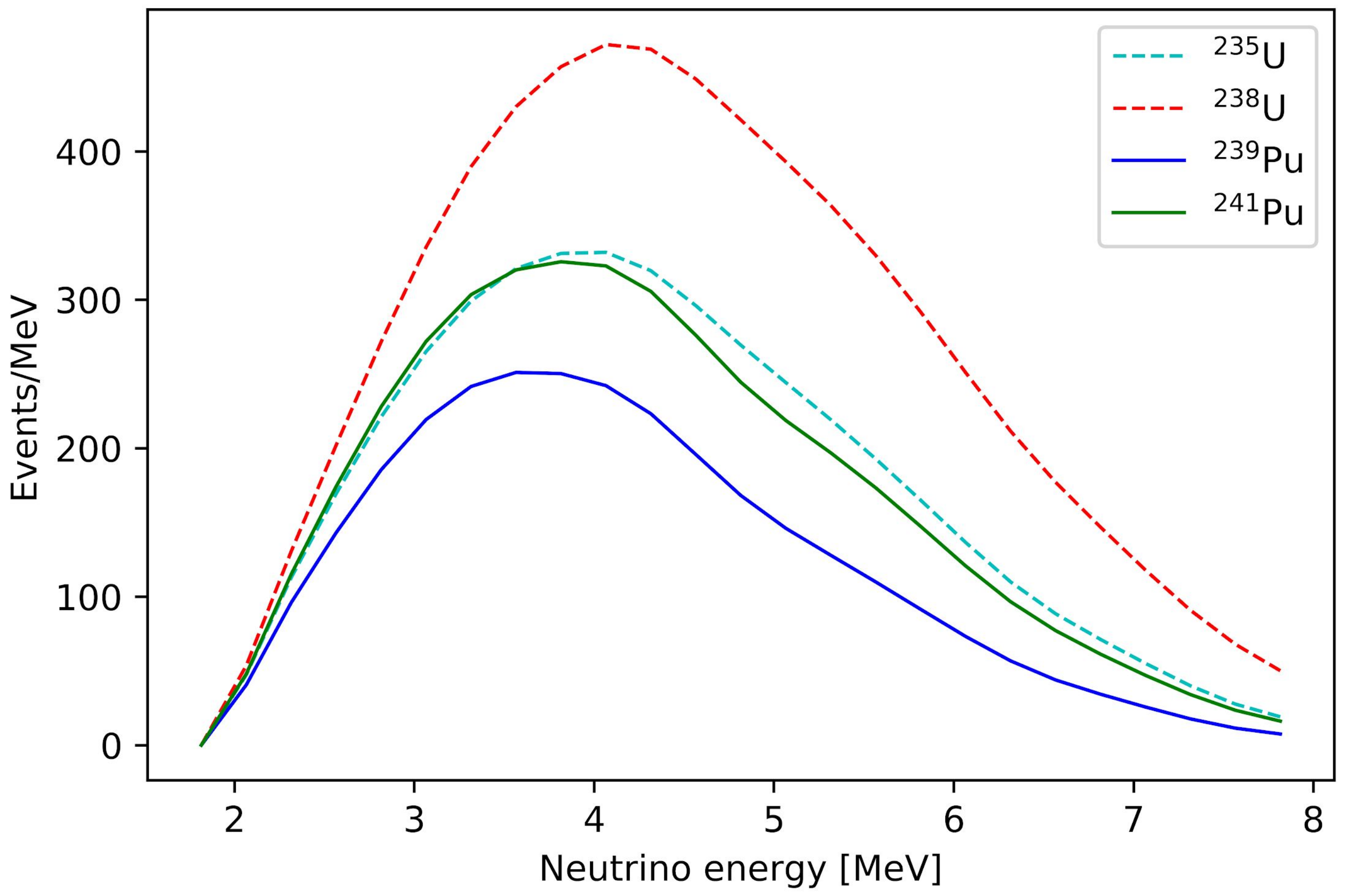

Fig. 2 (above)
IBD event number per kg of CH$_2$ per year at a 1 GW$_{th}$ reactor and at a distance of 10 m

Fig. 3 (below)
Energy spectra for uranium-235, uranium-238, plutonium-239, and plutonium-241

METHODS

To compute the neutrino counts and energy spectra, we use the cross sections and fluxes for reactor neutrinos from each isotope found in the reactor.

	IBD	CEνNS
Cross section	$\sigma = \frac{2\pi}{m_e^5 f^R \tau_n} E_e p_e$	$\frac{d\sigma}{dT}(E_\nu) = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$
Integration	$\int_{0.125\ \mathrm{MeV}}^{8\ \mathrm{MeV}} \sigma_{IBD}(E_\nu) f_I(E_\nu)\, dE_\nu$	$\int \int_{T_{min}}^{T_{max}} f_I(E_\nu) \frac{d\sigma}{dT}(E\nu)\, dT\, dE_\nu$
Normalization*	$N_I = t\frac{P}{E_I} M N_A \frac{2}{14} \frac{1}{4\pi L^2}$	

For both IBD and CEνNS, we chose a detector mass of 1 kg at a distance of 10 m away from a 1 GW$_{th}$ reactor over a period of 1 year.

*For CEνNS, the normalization factor is modified for the atomic mass of each potential target nuclei. The 2/14 factor is changed to 1/m for m atomic mass.

RESULTS

Figure 2 shows that the number of neutrinos produced by and detected from each isotope in a reactor through IBD differs significantly. Figure 3 illustrates the distinct energy spectra computed for each isotope via IBD. Figure 4 displays the neutrino event number above a given nuclear recoil energy threshold for various isotopes that could serve as target masses in detectors for CEνNS.

Threshold [eV]	Isotope								
	^{4}He	^{12}C	^{20}Ne	^{28}Si	^{40}Ar	^{74}Ge	^{127}I	^{132}Xe	^{133}Cs
0	4360*	13100	21800	30500	52800	104000	188000	201000	200000
10	4320*	12800	20900	28900	48900	91000	152000	161000	160000
100	4030*	10700	15900	20200	30400	42200	47200	48400	47600
1 000	2510*	3480*	3030*	2330*	1710*	294*	0.719*	0.185*	0.123*
10 000	141*	0.239*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*

Fig. 4
CEvNS event number per kg per year for Uranium-235 at a 1 GW$_{th}$ reactor and at a distance of 10 m as a function of isotope and recoil energy threshold. The corresponding event number for IBD in 1 kg of CH2 is 4360, as shown in Fig. 2. Event numbers lower than this are marked with an asterisk.

CONCLUSIONS

The same challenge that allowed CEνNS to evade detection for forty years dictates the efficacy of its use in experimental neutrino physics. For almost every potential target isotope we considered, CEνNS will yield a lower event number than IBD with recoil energies around the order of 1 keV or higher. Great advances have been made to detect the very small recoil energies of CEνNS, and with continued advancement, CEνNS will offer improved opportunities for new understandings of neutrino physics. Once detector technology catches up to theory, CEνNS can offer new insight into remote nuclear reactor and spent fuel monitoring, geoneutrinos, and neutrino physics.

REFERENCES

Akimov D. *et. al.* Sept 2017. DOI: 10.1126/science.aao0990

Carr R. *et. al.* Nov 2018. DOI: 10.1080/08929882.2019.1603007

Cogswell B. & Huber, P. Jun 2016. DOI: 10.1080/08929882.2016.1184531

Huber, P. Aug 2011. DOI:10.1103/PhysRevC.84.024617

Vogel, P. & Beacom, J.F. Apr 1999. DOI: 10.1103/PhysRevD.60.053003

Fig. 1.1 image credit to Fernandez, P. Feb 2017. DOI: 10.13140/RG.2.2.19649.56169

Fig. 1.2 image credit to Brice, S.J. *et. al.* Nov 2013. DOI: 10.1103/PhysRevD.89.072004

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