Reactor Anti-neutrino Emission Modelling for Nuclear Safeguards

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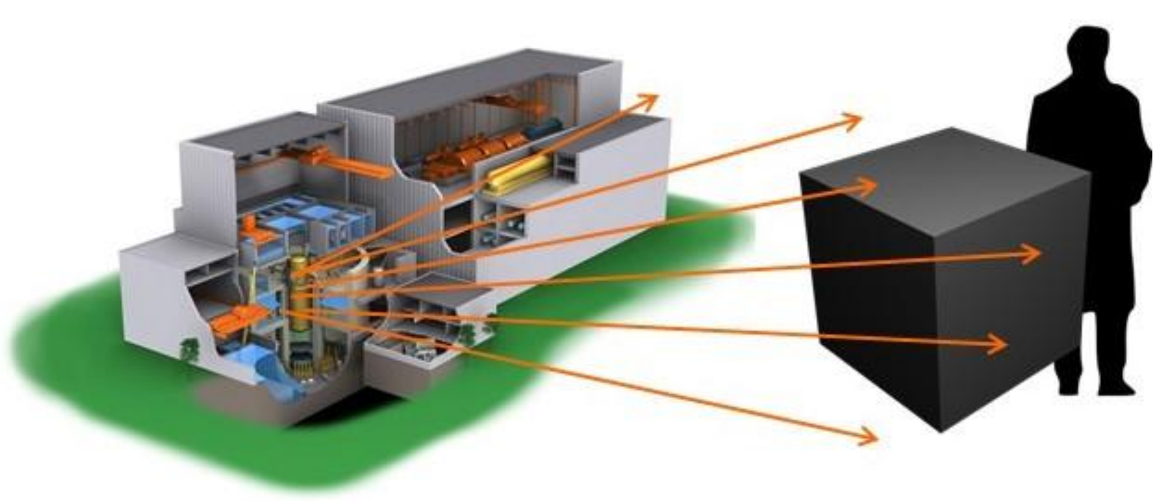
Motivation

Reactor anti-neutrino monitoring offers the potential for remote access to the workings of a fission reactor in real time. This is possible because anti-neutrino emissions from fission product beta-decays are correlated to the total power and fuel composition of a reactor. However, in order to interpret detector findings, a good understanding of expected anti-neutrino emissions is needed. Currently anti-neutrinos emissions are predicted by methods which do not take into account the time-dependent effects which are particularly important during reactor shutdown and startup. Comparing the current method to a more comprehensive approach including time-dependent effects will demonstrate the regimes where the equilibrium assumption is justified.



Ingredients of a Spectrum

Reactor anti-neutrino spectra are most commonly calculated by combining the frequency of the four main fissioning species in a reactor (^{235,238}U and ^{239,241}Pu) with anti-neutrino spectra calculated per fission.

This method assumes that the fission products whose beta-decays produce detectable antineutrinos are in equilibrium (so their production rate equals their beta-decay rate) and that transmutation from neutron capture on fission products is negligible.

In order to verify these assumptions, a typical equilibrium anti-neutrino emission calculation was compared to a time-dependent method using the best industrial software to predict anti-neutrino emission from the actual content of a reactor.

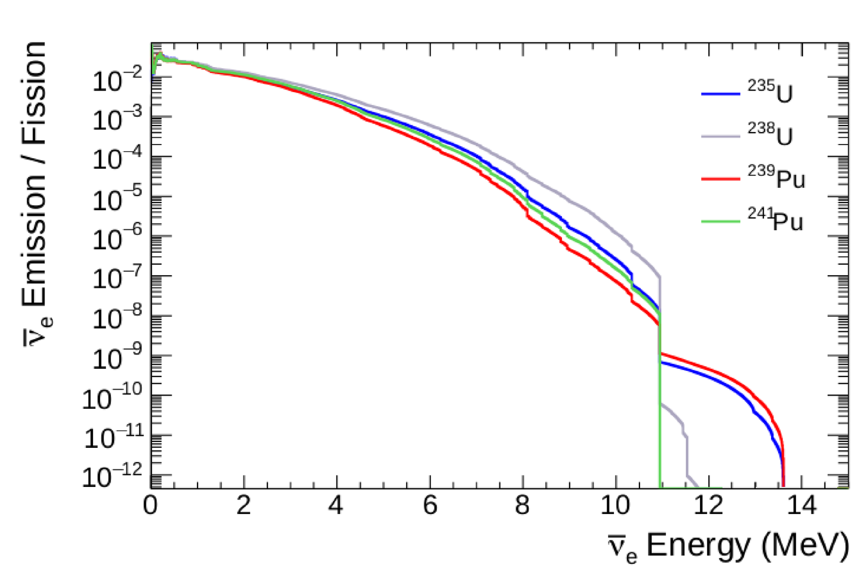


Figure 1: Differences in anti-neutrino emissions from the 4 main fissile isotopes

Anti-neutrinos from fuel software

Reactor irradiation of a Magnox fuel element was simulated by standard UK nuclear software (FISPIN). The isotopic composition of the fuel was predicted considering neutron capture on actinides, fission products, fuel additives and impurities as well as fission yields. This was compared to a 4 fission spectra approximation including only the fission yields. **The same beta-spectra were used in both calculations**, taken from the JEFF-3.1.1 nuclear database and combined with the fission products and fuel inventory output.

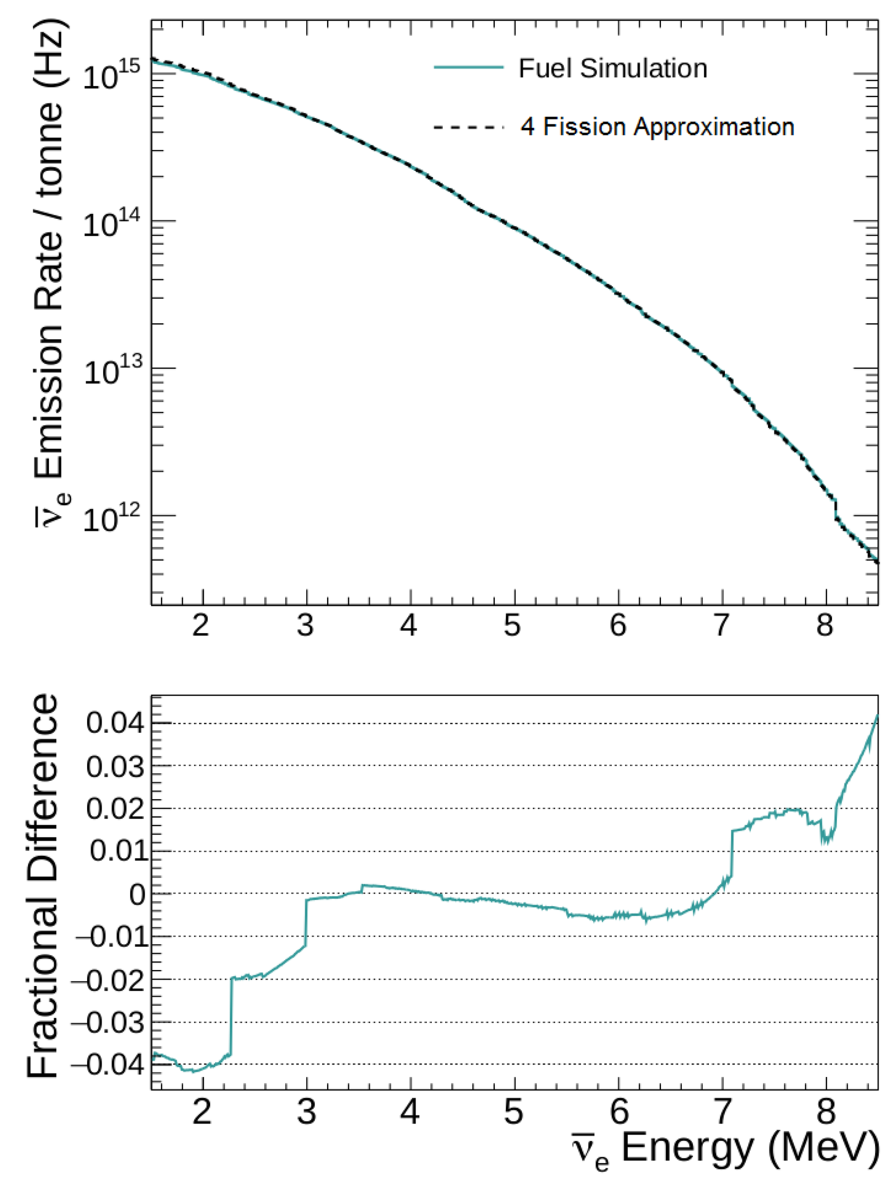


Figure 2: Comparison between the 4 fission spectra approximation and the full reactor calculation. the total integral over detectable anti-neutrinos is consistent to within 2%

Figure 2 considers fuel during the first few months of irradiation. Figure 3 shows that the two predictions converge over the lifetime of fuel in reactor. Further work will demonstrate whether the differences lie within uncertainties and explore highly time-dependent regimes such as reactor startup and shutdown.

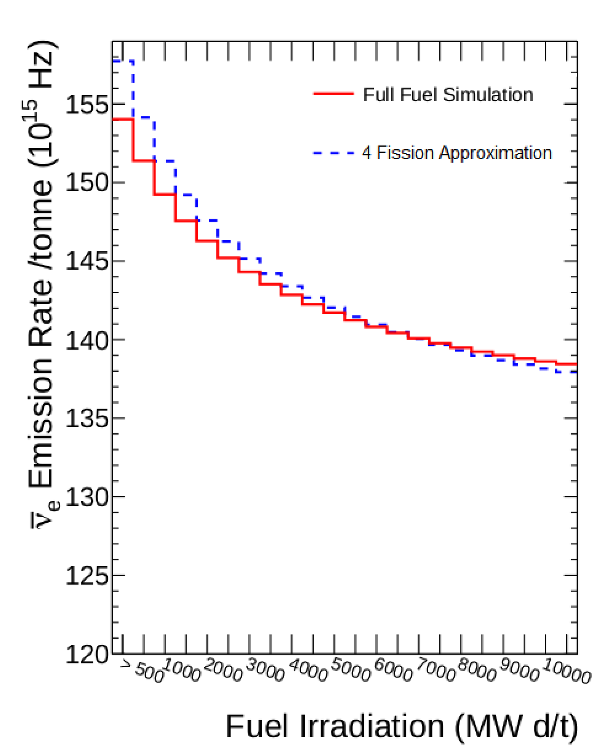


Figure 3: Total detectable anti-neutrinos predicted by the fuel simulation and 4 fission spectrum approximation converge as fuel time in reactor increases

Unknown Spectral Data

Not all beta-decaying nuclides from fuel have well measured beta-spectra due to the short half-lives of high energy emitters. These are expected to contribute around 10% of anti-neutrino emissions.

The missing spectra were approximated by taking the spectral shape of a known anti-neutrino decay adjusted to match the endpoint energy of the missing nuclides. Two such substitutions were explored and compared to the known anti-neutrino spectra. The chosen isotopes (^{24}F, E_β = 14.7 MeV and ^{122}Cd, E_β = 3 MeV) had single transition decays with short half-lives. The difference in outcome from two similar decays suggests the choice of individual spectral shapes has significant effects on the resulting per-fission spectrum.

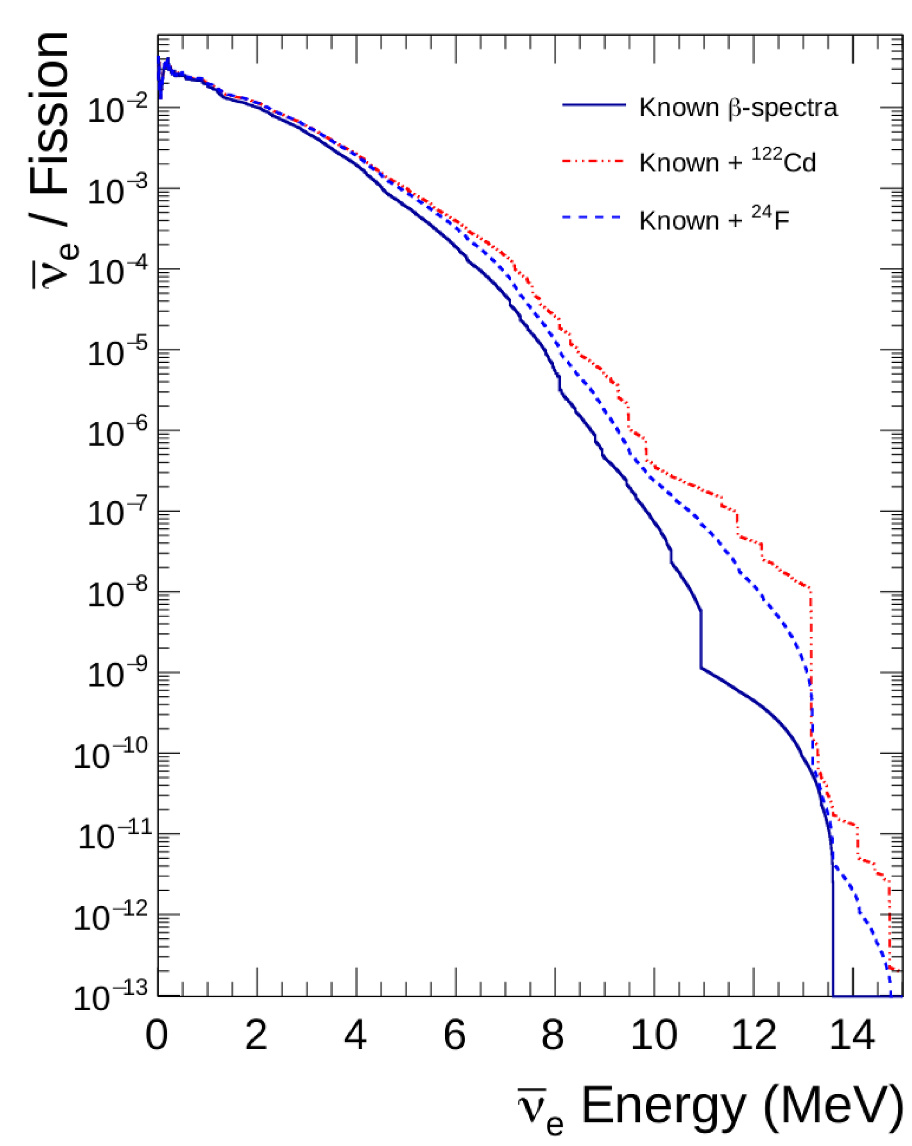


Figure 4: Difference between ^{239}Pu anti-neutrino emissions calculated from known beta-spectral data only and two theoretical spectra where missing data has been filled in with spectral data from ^{24}F and ^{122}Cd

Outlook

- Investigate scenarios where time-dependent effects are significant (startup, shutdown)
- Confirm differences between calculations are within uncertainties

Summary

- Standard anti-neutrino calculation verified against full fuel simulation
- Good agreement suggests current model assumptions are valid
- Choice of beta-spectrum shape has substantial effect on anti-neutrino spectra of unmeasured decays

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