Modelling Reactor Antineutrino Emissions for Nuclear Safeguards

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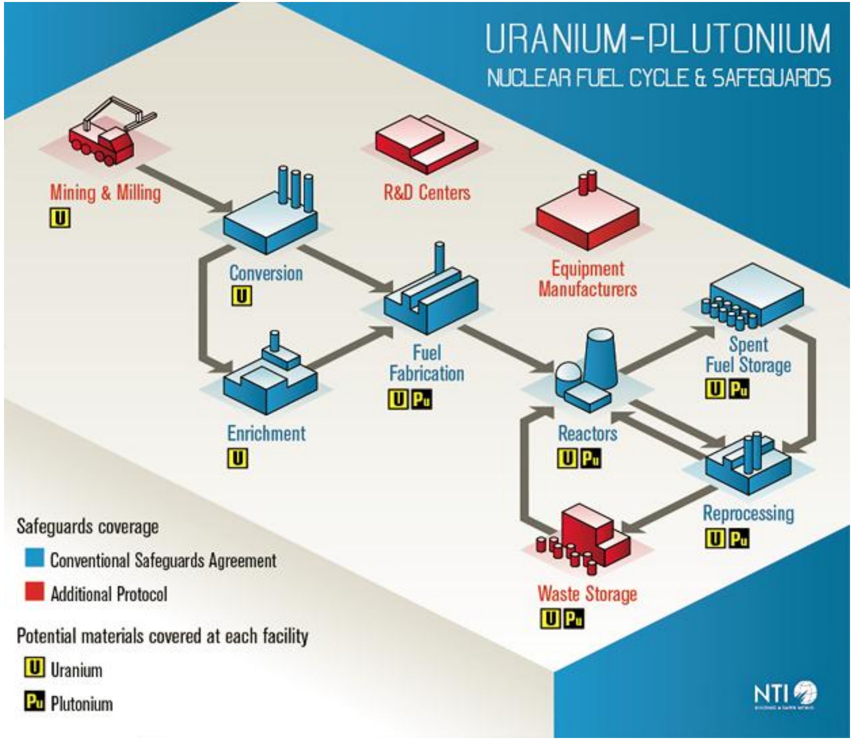
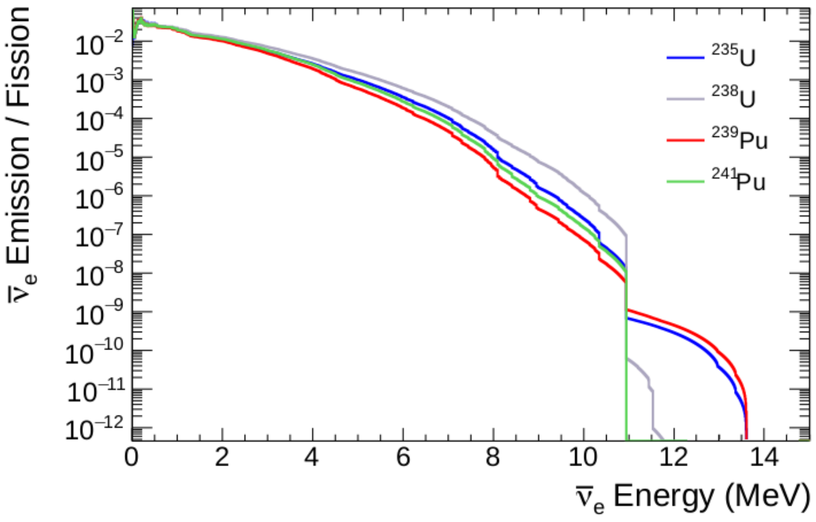
Nuclear Safeguards Monitoring

- Safeguards: **measures to verify compliance with the Non-Proliferation Treaty**
- Monitoring: verifies operator declarations of nuclear material
- Difficult to monitor fuel during irradiation in reactors
  - Fuel can spend ~2-10 years in reactor
  - Fuel accounting before and after irradiation



Anti-neutrino Reactor Monitoring

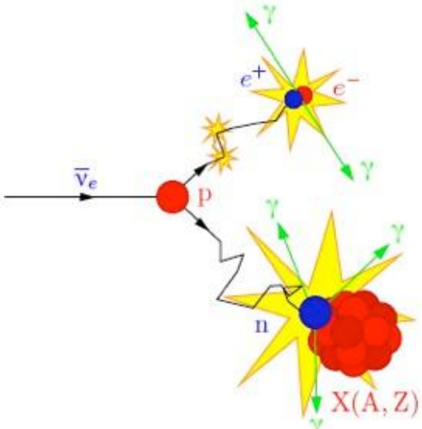
- Large production in fission reactors
  - Beta-decaying neutron-rich fission products
  - ~10^{20}/s/GW_{TH}
- Very low interaction rate with matter
  - Can't be shielded
  - Difficult to detect
- Real-time reactor information
  - Approximate power
  - Fissile isotope composition
- IAEA key detector suggestions:
  - Tonne scale
  - Portable

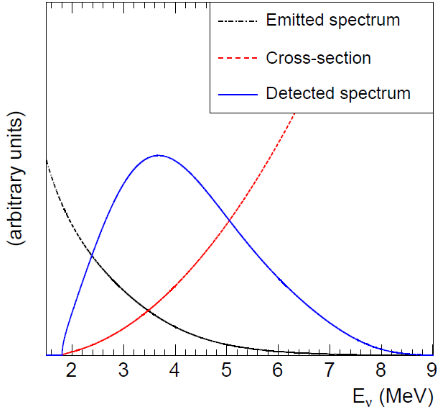


Per-fission anti-neutrino spectrum variation between fissile nuclides

Anti-neutrino Detection

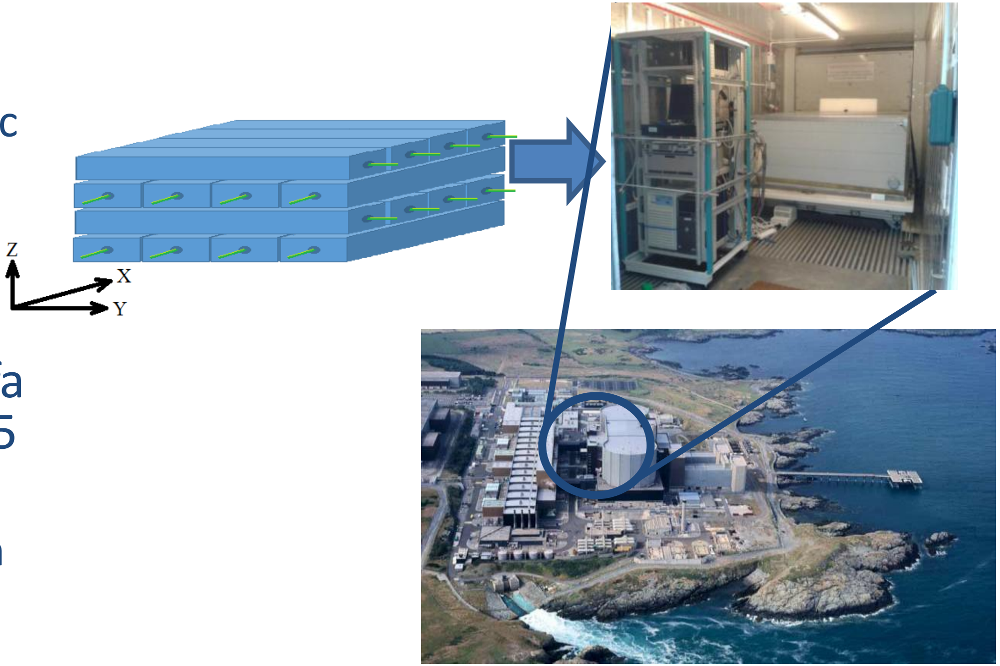
- Inverse beta decay (IBD)
  - $\overline{\nu}_e + p \longrightarrow n + e^+$
  - 1.806 MeV threshold
  - Reactor anti-neutrino energy: 0-15 MeV
  - Cross-section σ rises with $\overline{\nu}_e$ energy
  - "Double coincidence" reduces background





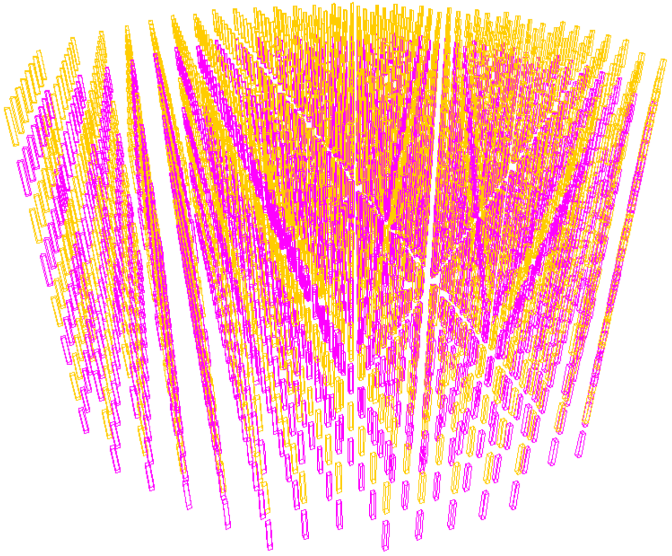
The VIDARR Detector Prototype

- Detector details:
  - Transportable by lorry
  - 70 layers of instrumented plastic scintillator bars
    - ~1 tonne active mass
  - Gadolinium-doped sheets for neutron capture
- Prototype demonstrated at Wylfa nuclear power station 2014-2015
  - 60 m baseline
  - Increase of 30 events/day when reactor in operation



Modelling the Wylfa 1 Reactor

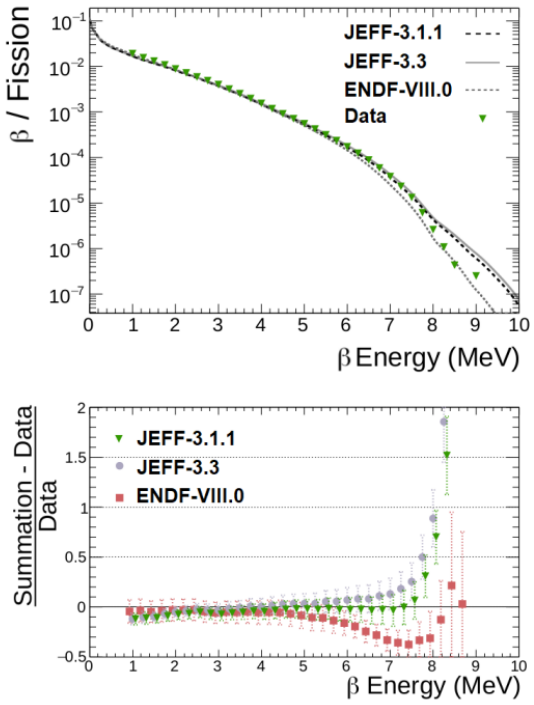
- Need to know anti-neutrino flux at detector
- Flux calculator program developed
  - Fuel model combined with geometric model
  - Could be adapted for other experiments eg. WATCHMAN/AIT
    - Beyond scope of PhD
- Data available from operator
  - Daily total power history
  - Monthly fuel status data for full reactor
- Geometric model positions fuel elements w.r.t. detector



Visualisation of fuel element arrangement in a Magnox core

Reactor Anti-Neutrino Emissions

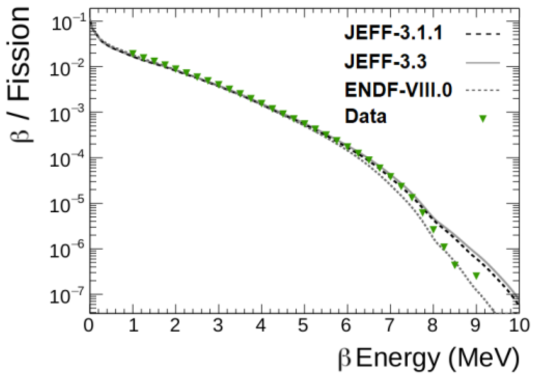
- **Currently three approaches**
- Convert experimental beta spectrum measurements
  - Spectra measured from irradiated fissile isotopes
  - Converted into anti-neutrino spectra by dividing into “virtual beta branches”
- Calculate from nuclear data (“Summation”)
  - [fission yield] × [per-isotope anti-neutrino spectra]
  - ~10% of spectrum has unknown decay data
- **Both assume decay rate = production rate**
- MC reactor models
  - Use available reactor modelling software
  - Data from nuclear databases
  - **Includes time-dependent effects**

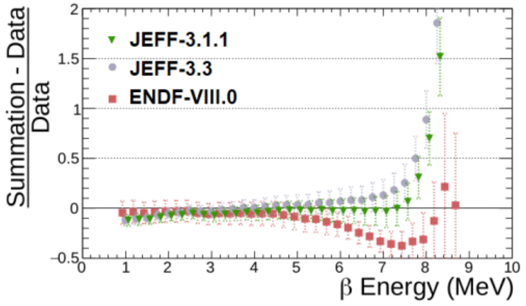


^{235}U per-fission beta spectra

Reactor Anti-Neutrino Emissions

- **Fuel modelled using standard UK reactor software**
- Supporting work on equilibrium “summation” calculations
  - Calculating beta and anti-neutrino spectra using different nuclear databases
    - JEFF-3.1.1, JEFF-3.3, ENDF-VIII.0
    - Compared with experimental data
    - Compared with current standard
    - Model unknown spectra with substitute shape data
  - **Gives insight into model-based uncertainties on flux calculation**

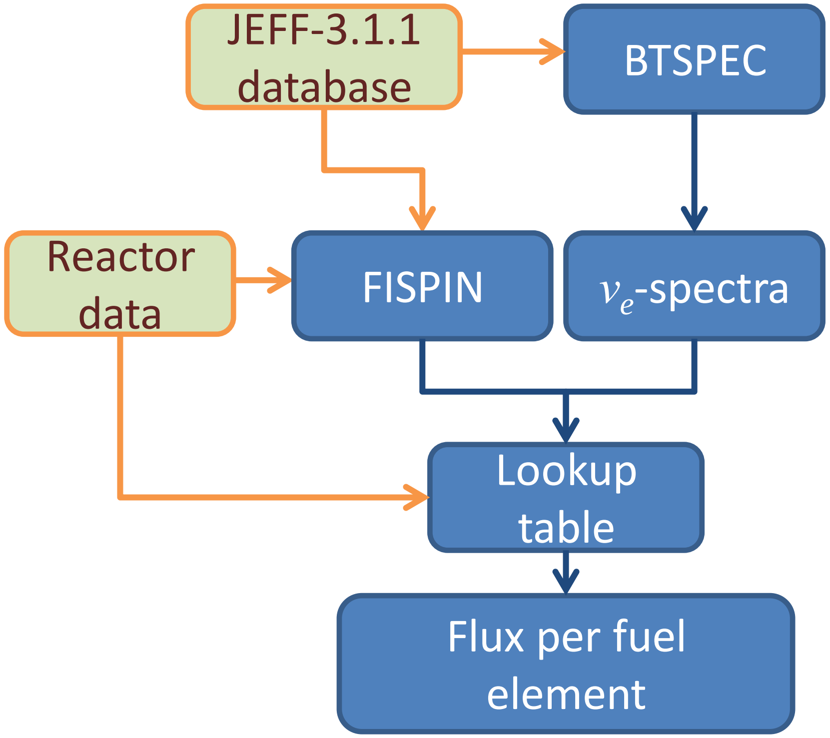




^{235}U per-fission beta spectra

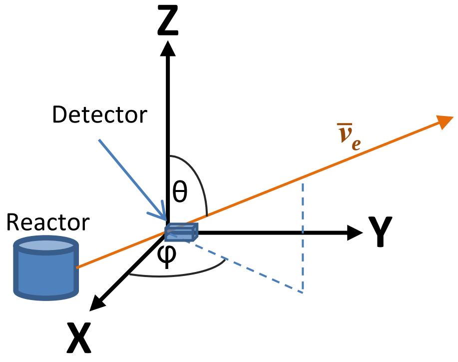
Wylfa Fuel Model

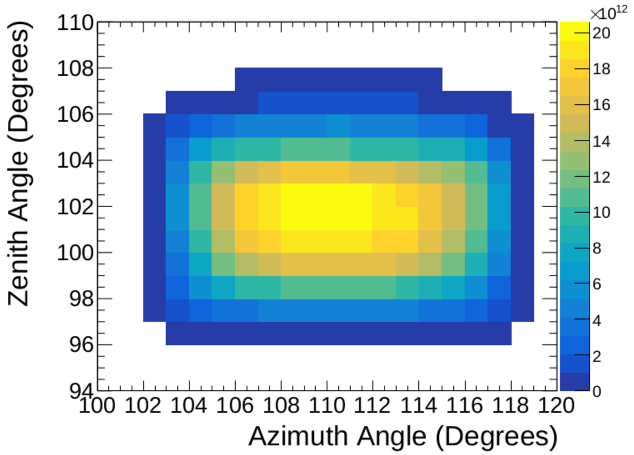
- Anti-neutrino emission calculation by NNL
- Uses standard UK nuclear software
  - FISPIN (fuel irradiation)
  - JEFF-3.1.1 (fission & beta decay data)
  - BTSPEC (calculates beta [anti-neutrino] spectra)
- Combines FISPIN fuel simulation with per-isotope anti-neutrino spectra
- Time dependent effects included
- Anti-neutrino emission lookup table over fuel status
- Flux at detector calculated per-element and integrated over all elements



Flux Calculator Output

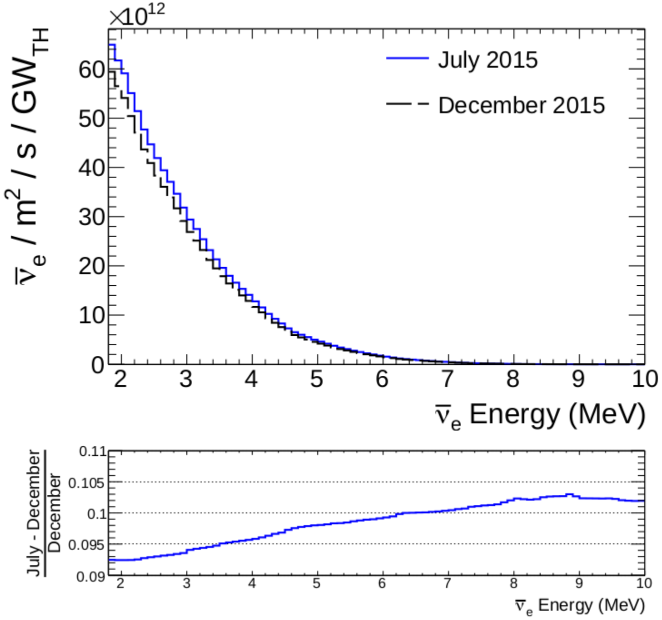
- Flux calculated across face of detector
- Binned by anti-neutrino energy and direction
- 18 monthly "snapshots" generated
  - July 2014 – December 2015
- Predicted IBD consistent with data within uncertainties





Anti-neutrino Spectrum Evolution

- Varies between months
  - Evolves with fuel
  - Plutonium grows with irradiation
  - Plutonium produces fewer $\bar{\nu}_e$ per fission than Uranium
- Flux evolution over time ongoing work
- Aim to link fuel evolution with flux evolution
  - Goal: fuel inventory from anti-neutrino measurement



Antineutrino flux at the Wylfa Detector predicted for two different months

Summary

- Comprehensive model of Wylfa reactor 1 developed
  - Predicted IBD rate consistent with data within uncertainty
  - Adaptable to WATCHMAN/AIT
- Model output and supporting data to be analyzed
  - Uncertainties on flux calculation
  - Evolution of anti-neutrino spectrum with fuel
  - Key nuclides missing beta decay data