The Clatterbridge Cancer Centre NHS
NHS Foundation Trust

University Hospitals Coventry and Warwickshire NHS
NHS Trust

UCL

Background Neutron Scatter Modelling in Proton Beam Therapy

Sarah Baker

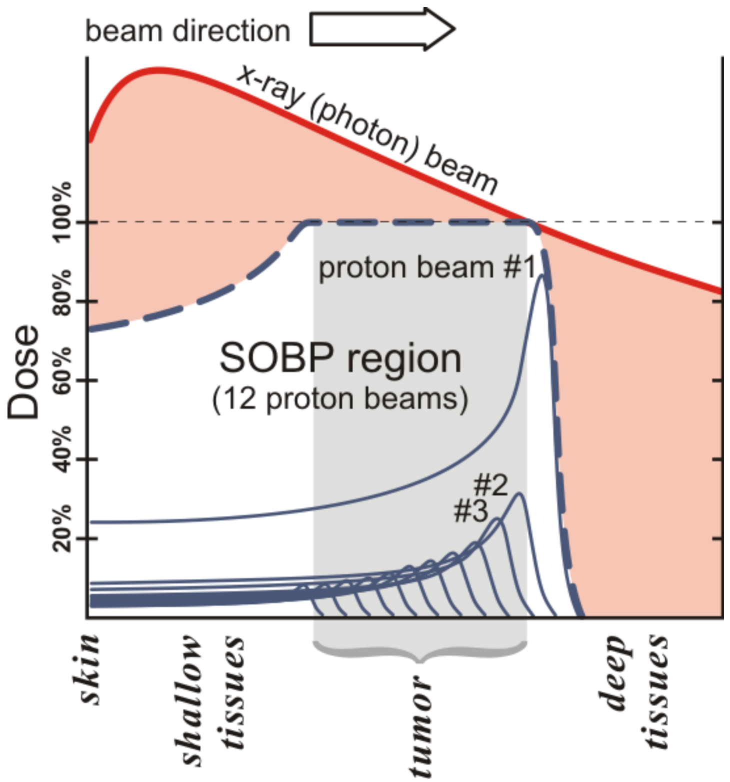
16th June 2016

Talk Overview

- Project Rationale and Outline
- Equipment
- Results
  - **Part 1: Neutron response of a plastic scintillator**
  - **Part 2: Comparison to neutrons from californium 252**
  - **Part 3: Neutron production at Clatterbridge Cancer Centre**
- Conclusions and Future Plans

Rationale: Proton Therapy

- Advanced radiotherapy using protons, rather than X-rays
- Maximum dose in the final few millimetres of the proton tracks (Bragg peak)
  - Bragg peak position dependent on the energy of the incident proton
  - Sharp distal dose fall-off
- Advantages:
  - Treatments close to critical organs such as head and necks
  - Paediatrics - reduction of induced secondary cancers in later life



Rationale: Neutron Production

- Proton beams interact with the beam-line and within the patient to produce secondary radiation
  - Neutrons can cause significant biological damage
- Neutron damage to tissues is strongly dependent on neutron energy and flux
- Spectroscopy of secondary neutrons would permit reduction of neutron scatter dose
  - Optimisation of beam-line arrangements
  - Improvements to dose delivery methods
  - Shielding of sensitive equipment
  - Reduction of risk of neutron induced secondary cancers

Project Outline: Remit

- UCL have developed a scintillator to measure the energy resolution and spread of a proton beam:

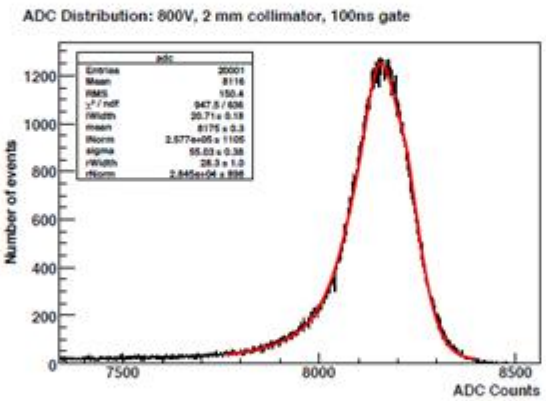
An optical module designed for the SuperNEMO experiment has measured the 60 MeV proton beam at Clatterbridge with an energy resolution of:

1.58 ± 0.27 % FWHM
(for 40 MeV "visible" energy)

↓

simple extrapolation:
0.7 % FWHM @ proton imaging energy (300 MeV)

Limit on energy spread of Clatterbridge beam:
FWHM (60 MeV) < 1.47% @ 90% CL



Source: Seminar by Anastasia Basharina-Freshville, UCL

Project Aim: Model the scintillator response to neutrons

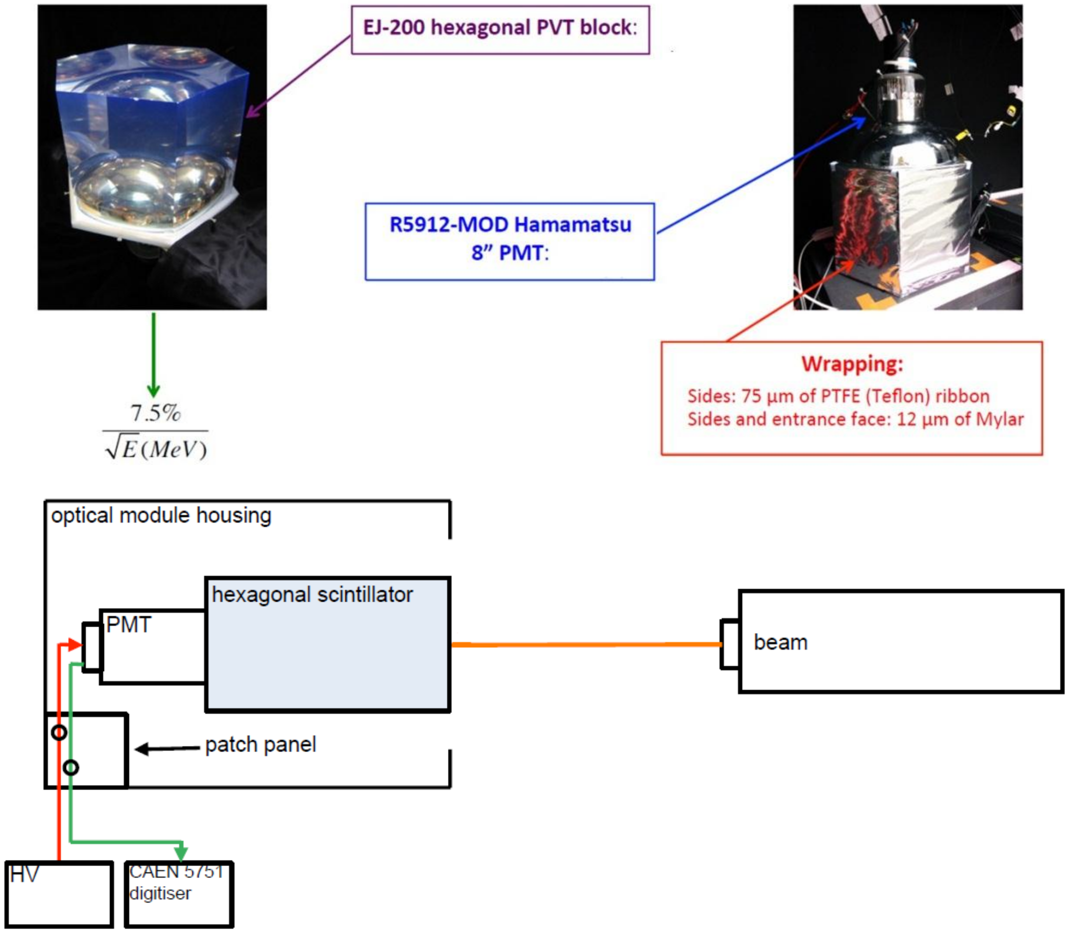
Project Outline: Particle Interactions

- Neutrons uncharged so interact with atomic nuclei
  - Scattering (elastic and inelastic)
  - Absorption (fission and capture)
- Neutron cross sections are strongly dependent on energy
  - Typically higher at lower energies
  - Detection often requires 'moderators' to reduce neutron energy via scattering – hydrogen is particularly effective
- Full simulation requires other relevant particle interactions (proton, γ, e-, e+ ...)
- Detector scintillation properties and resolution effects must also be considered

Equipment: Monte Carlo Simulation

- Simulation of physical processes using random sampling of probability distributions
- Monte Carlo in medical physics:
  - Event generation
  - Beam-line and detector simulation
- Geant4 used to generate input particle spectra and to model the scintillator
  - Applications in particle, nuclear, accelerator and dark matter physics
  - Provides access to particle data libraries
  - Must consider which process models and energies are important

Equipment: Scintillator and PMT



- Plastic scintillator Polyvinyl toluene (PTV) hexagonal block
- Wrapped in reflective material
- Coupled to a photo-multiplier tube (PMT)
- Irradiated with beam of particles

Source: Seminar by Anastasia Basharina-Freshville, UCL

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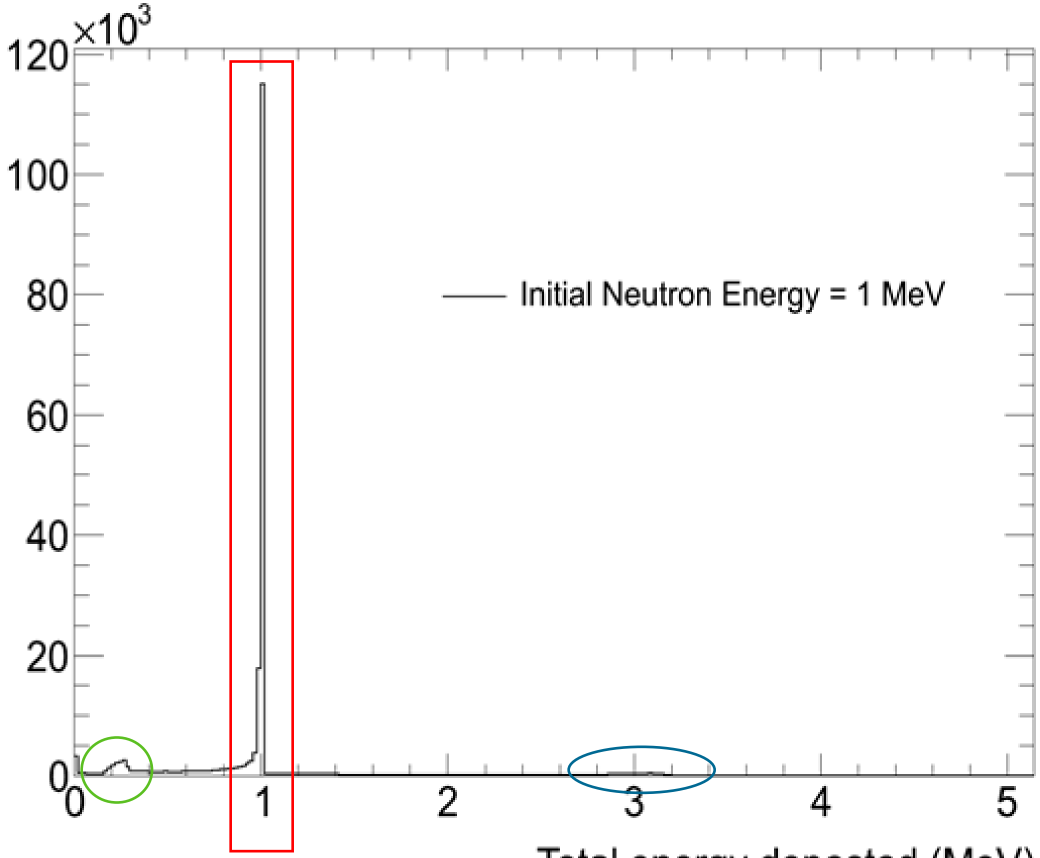
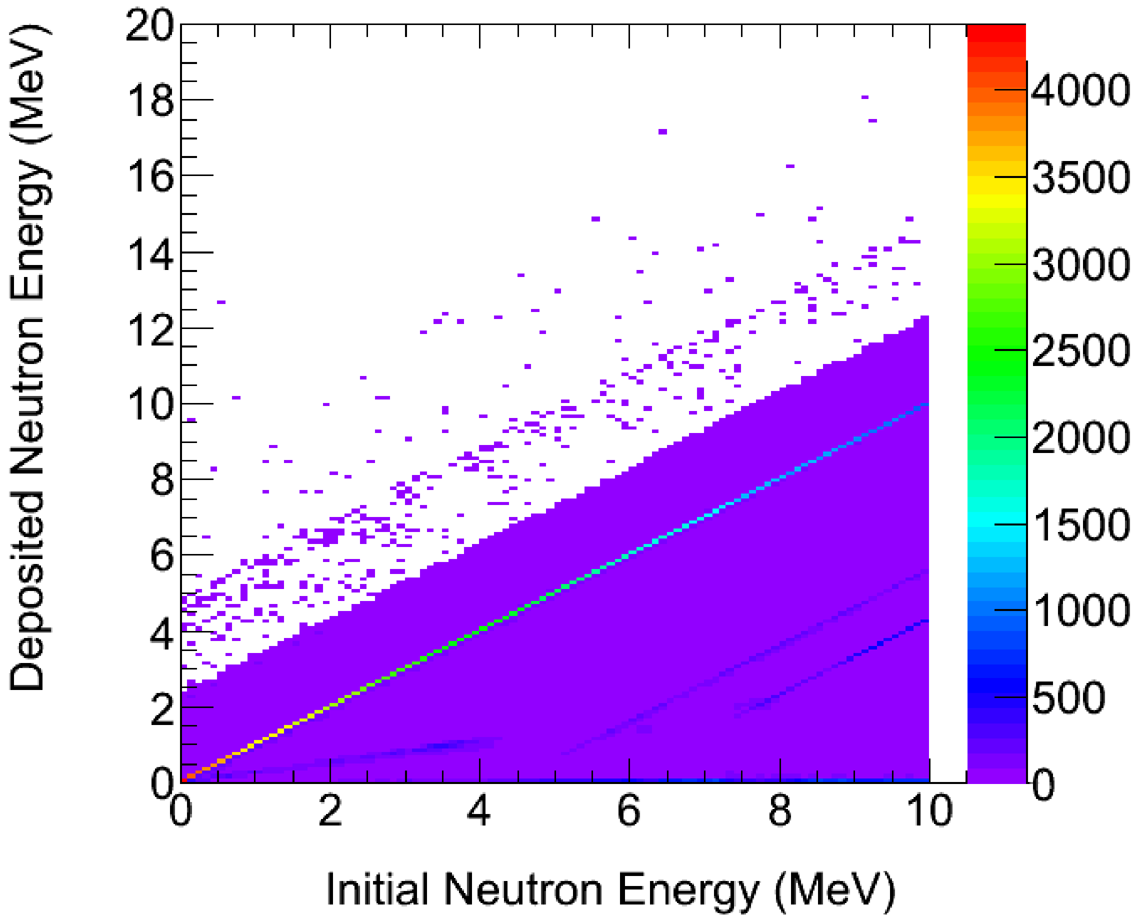
Results Part 1: Monoenergetic Beam



- Peak at 1 MeV - neutron energy fully deposited in scintillator (hydrogen scattering)
- Scatter from C12 atom
- 2.2 MeV gamma produced in neutron capture for hydrogen

Results Part 1: Polyenergetic Beam



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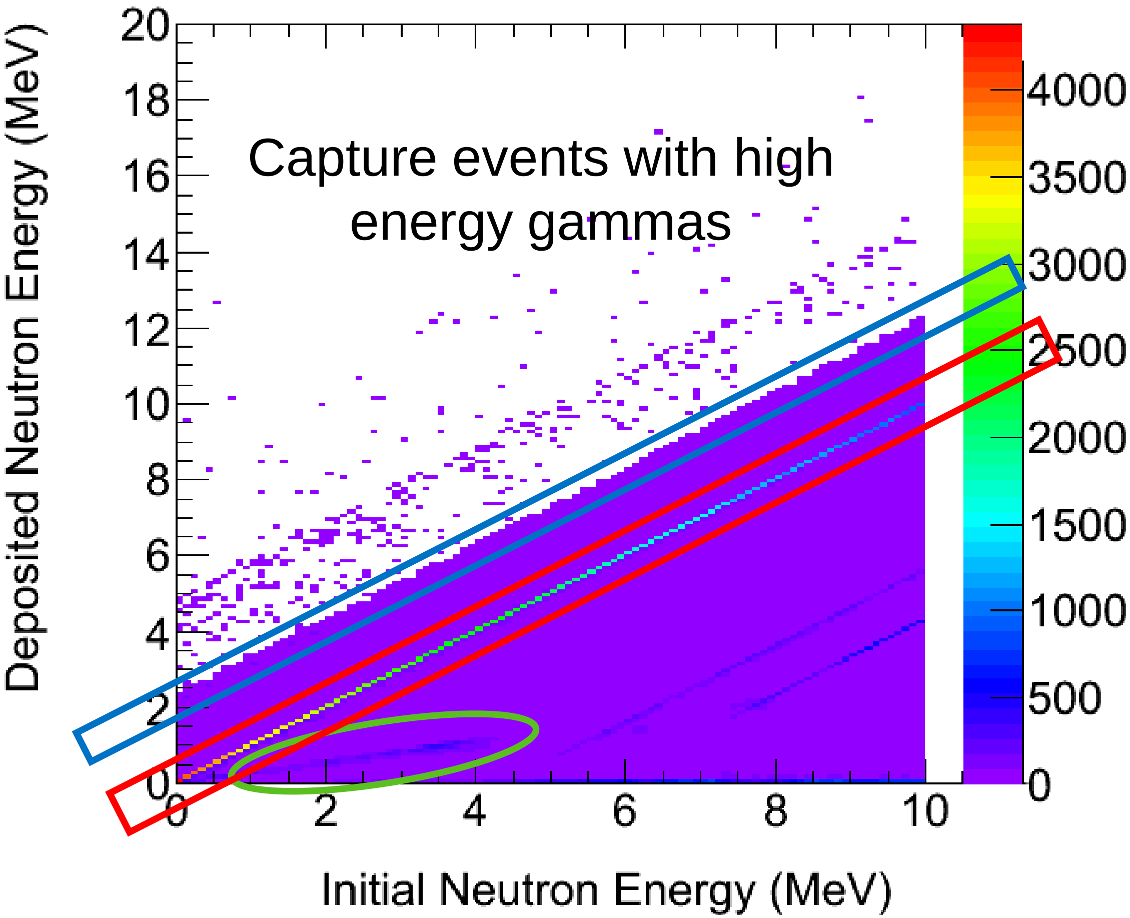

- Peak at 1 MeV - neutron energy fully deposited in scintillator (hydrogen scattering)
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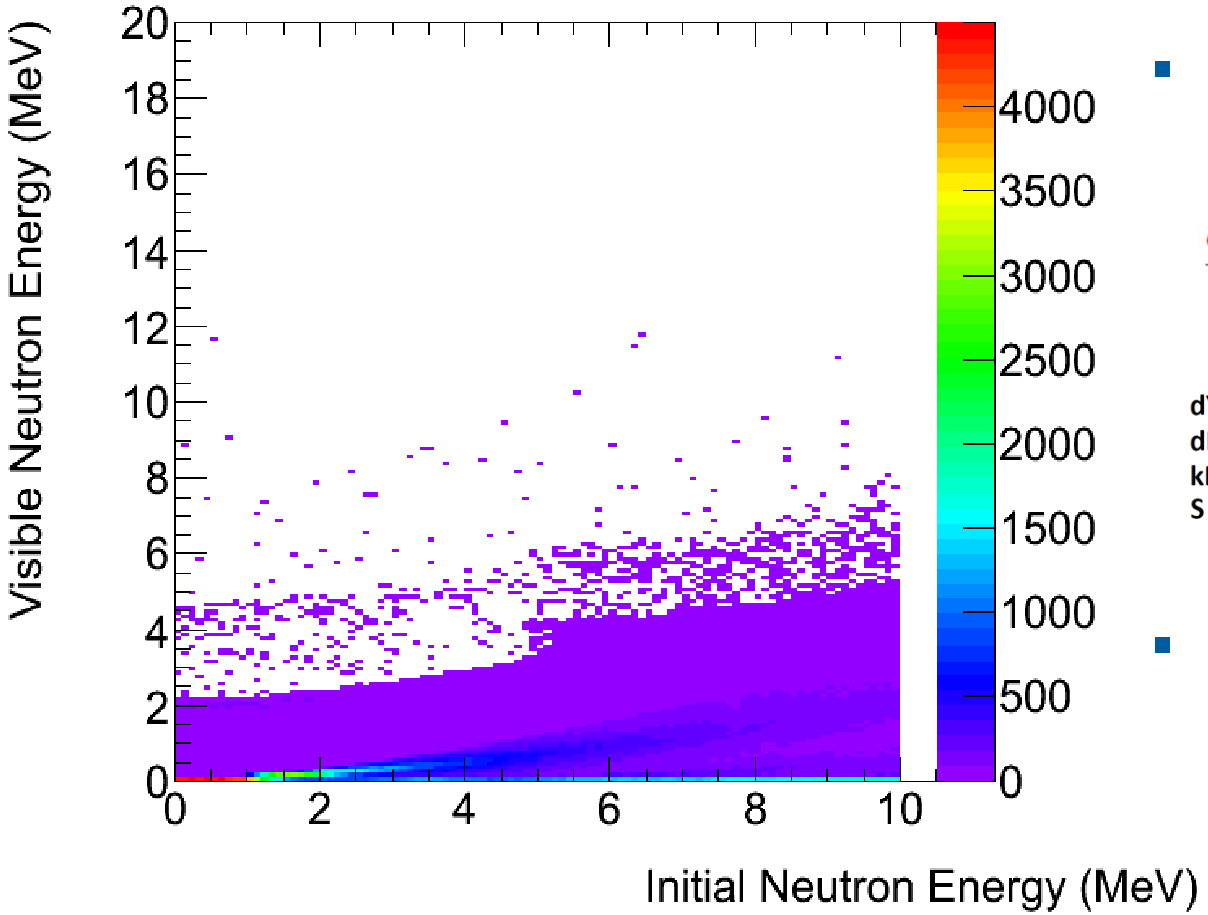
Results Part 1: Quenched Energy



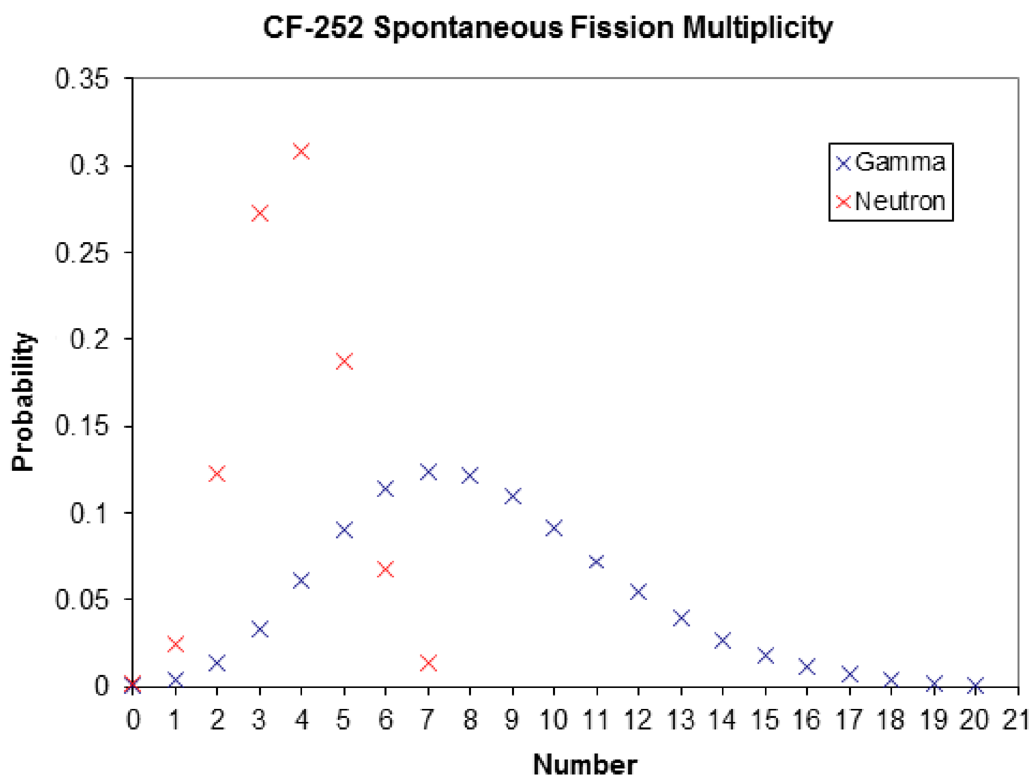
- Light yield is non-linear (quenched) - Birks law:

$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

dY/dx	light yield per unit path length
dE/dx	energy lost by particle per unit path length
kB	relates density of ionisation to energy loss
S	absolute scintillation efficiency

- Neutrons transfer energy to C12 and hydrogen

Results Part 2: CF-252 Gamma/Neutron Multiplicity (FREYA)



- Test Monte Carlo using a Californium source
- CF-252 emits gammas and neutrons via spontaneous fission
- Spontaneous fission not well handled by Geant4
- Alternative generator data (FREYA) used to create a bespoke CF-252 generator

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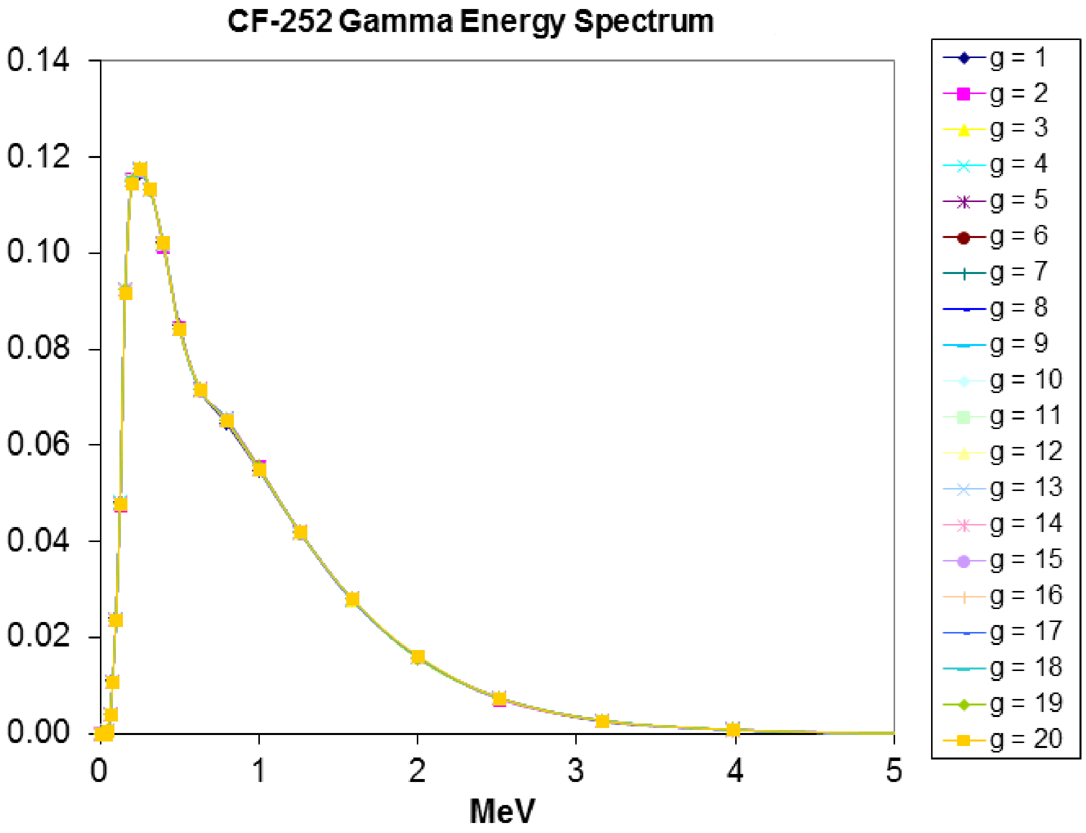
Results Part 2: CF-252 Gamma Spectrum (FREYA)



- Multiplicities and spectra combined to create a probability based particle generator to recreate the spontaneous fission
- Does not account for correlations

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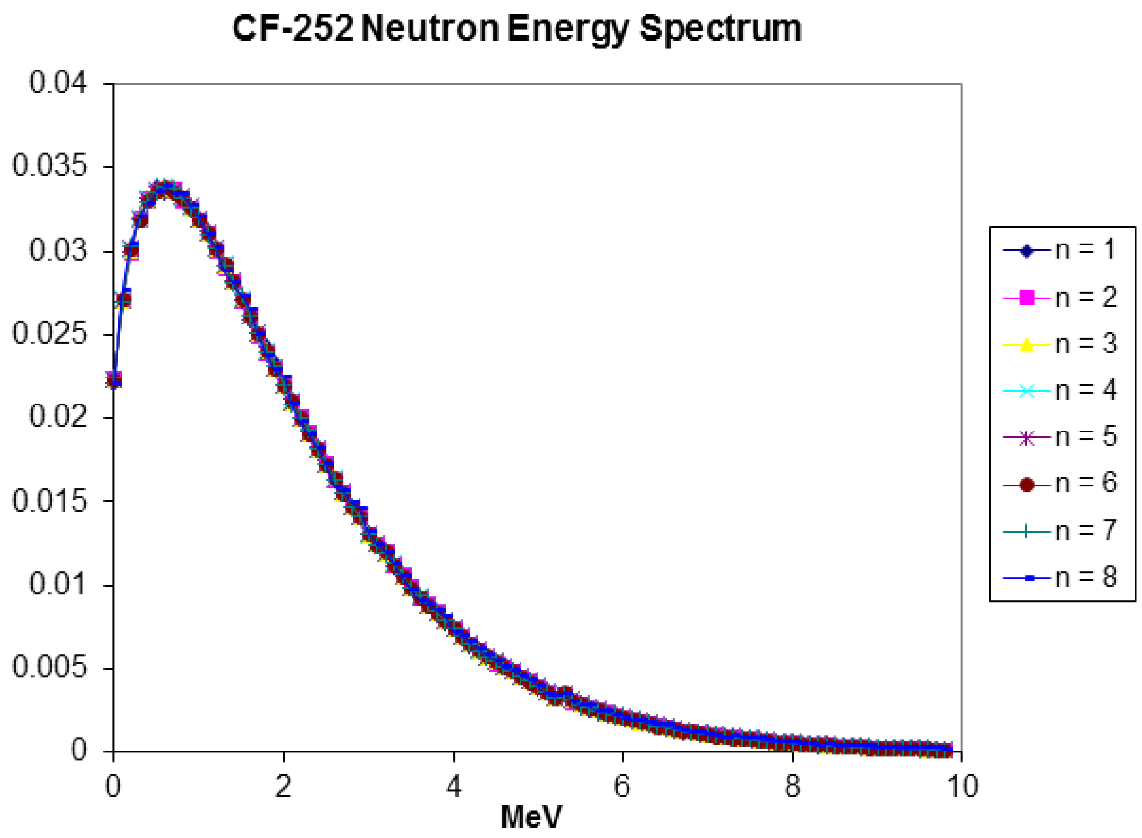
Results Part 2: CF-252 Neutron Spectrum (FREYA)



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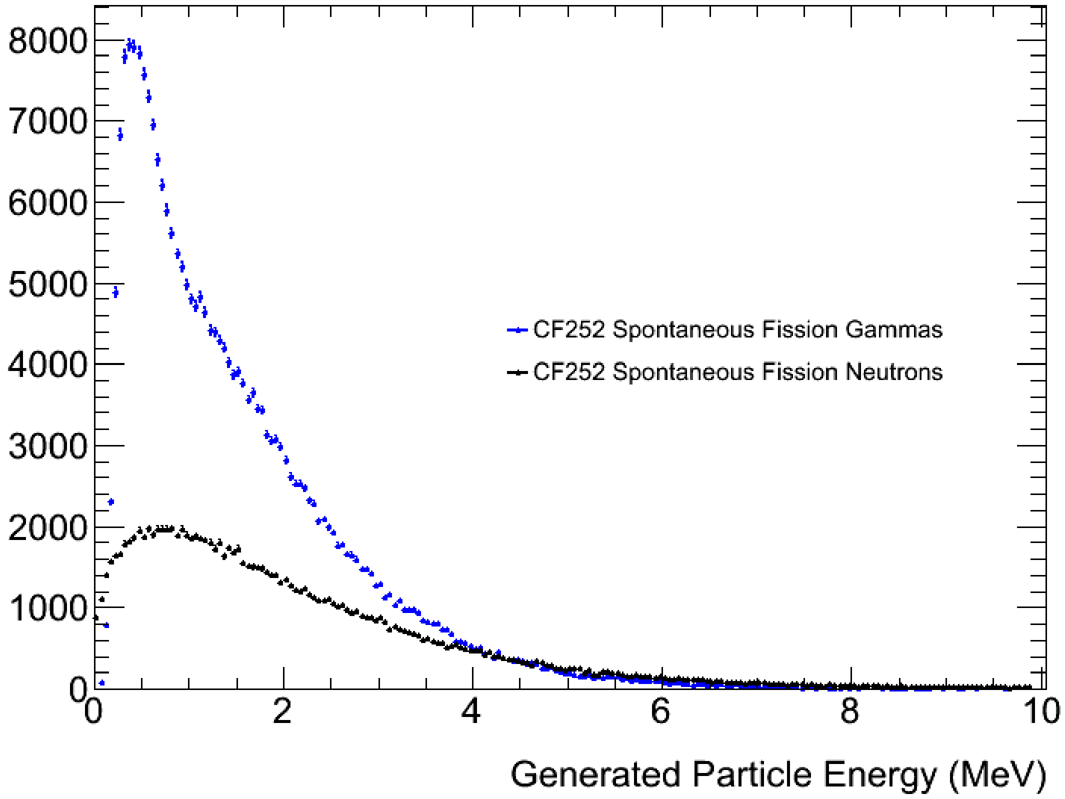
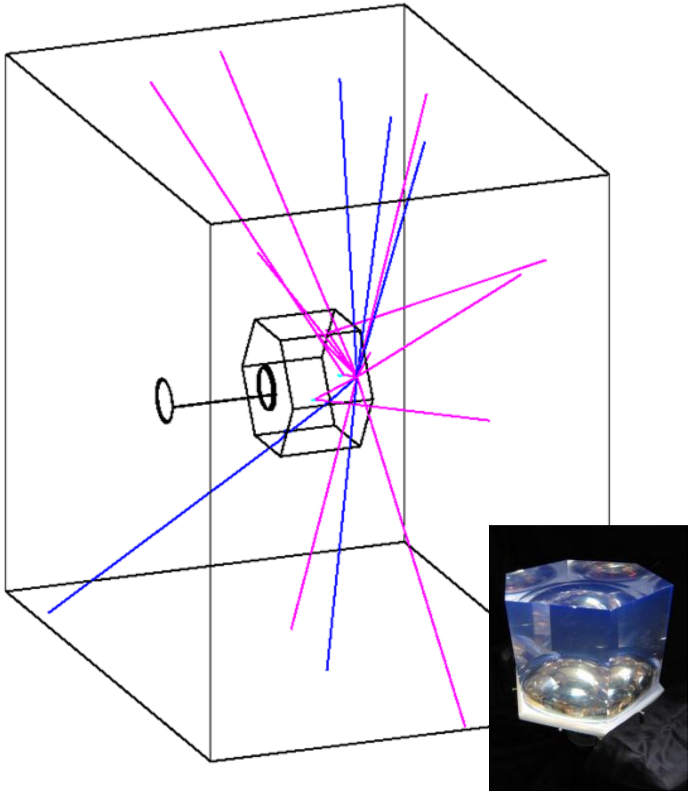
- Does not account for correlations

Results Part 2: CF-252 Generator Spectrum





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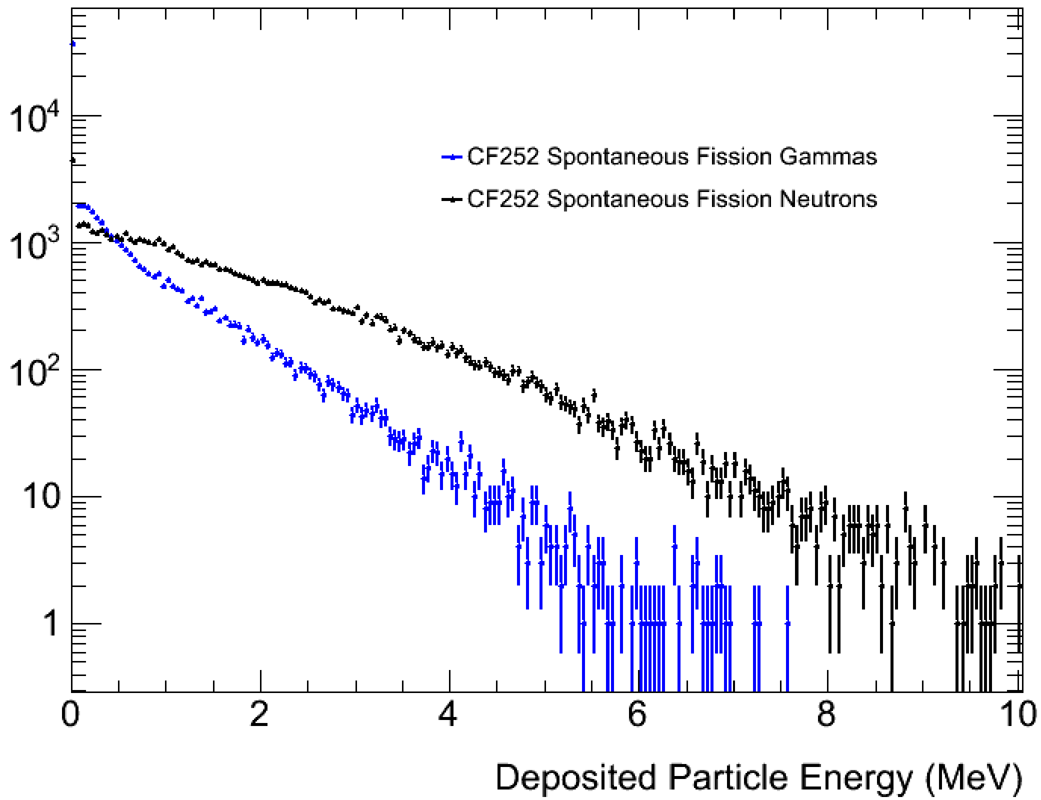
Results Part 2: CF-252 Deposited Energy



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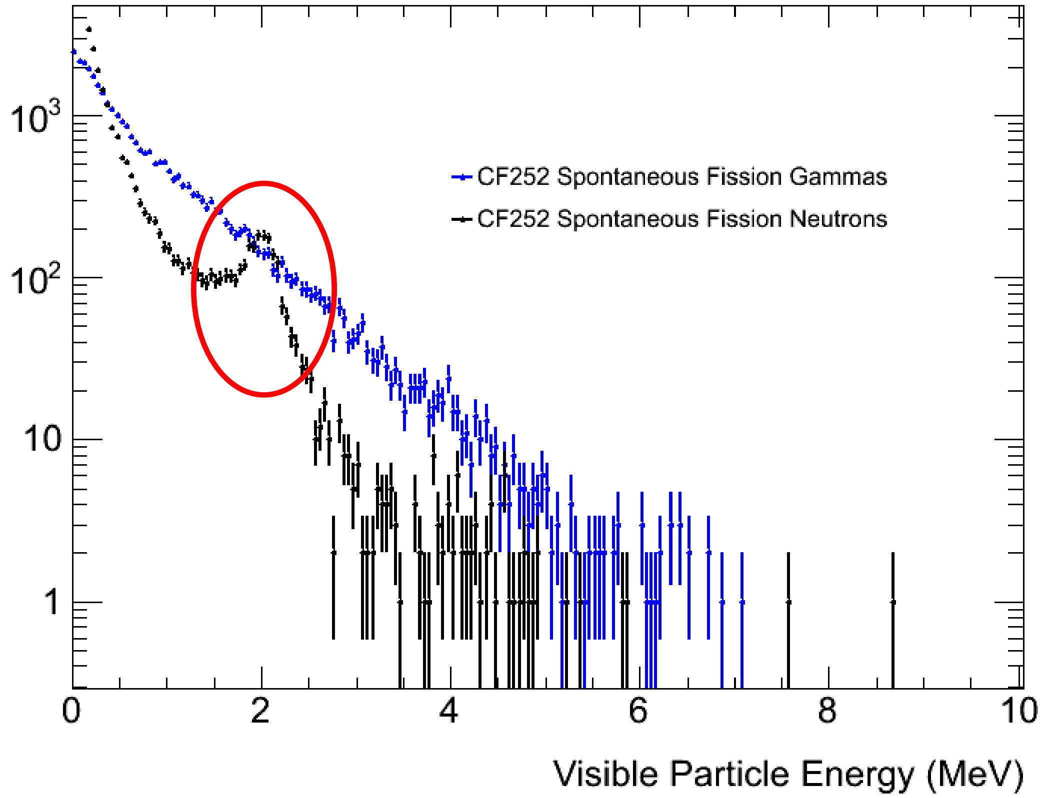
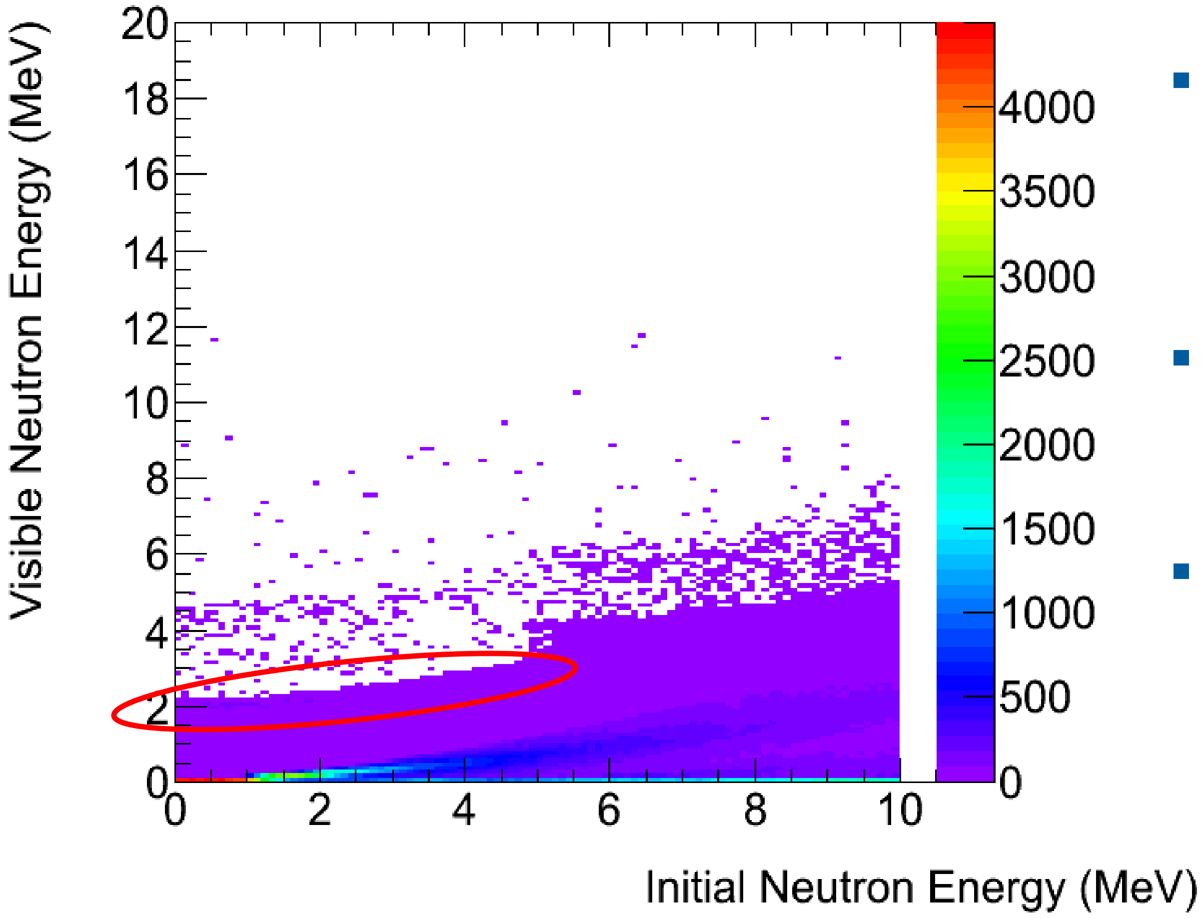
Results Part 2: CF-252 Quenched Energy



- Peak at neutron ~ 2 MeV in CF-252 visible energy spectrum
- Effect of the quench modelling?

Results Part 2: CF-252 Deposited Energy



- Peak at neutron ~ 2 MeV in CF-252 visible energy spectrum
- Effect of the quench modelling?
- Quenching of the 2.2 MeV gamma from neutron capture?

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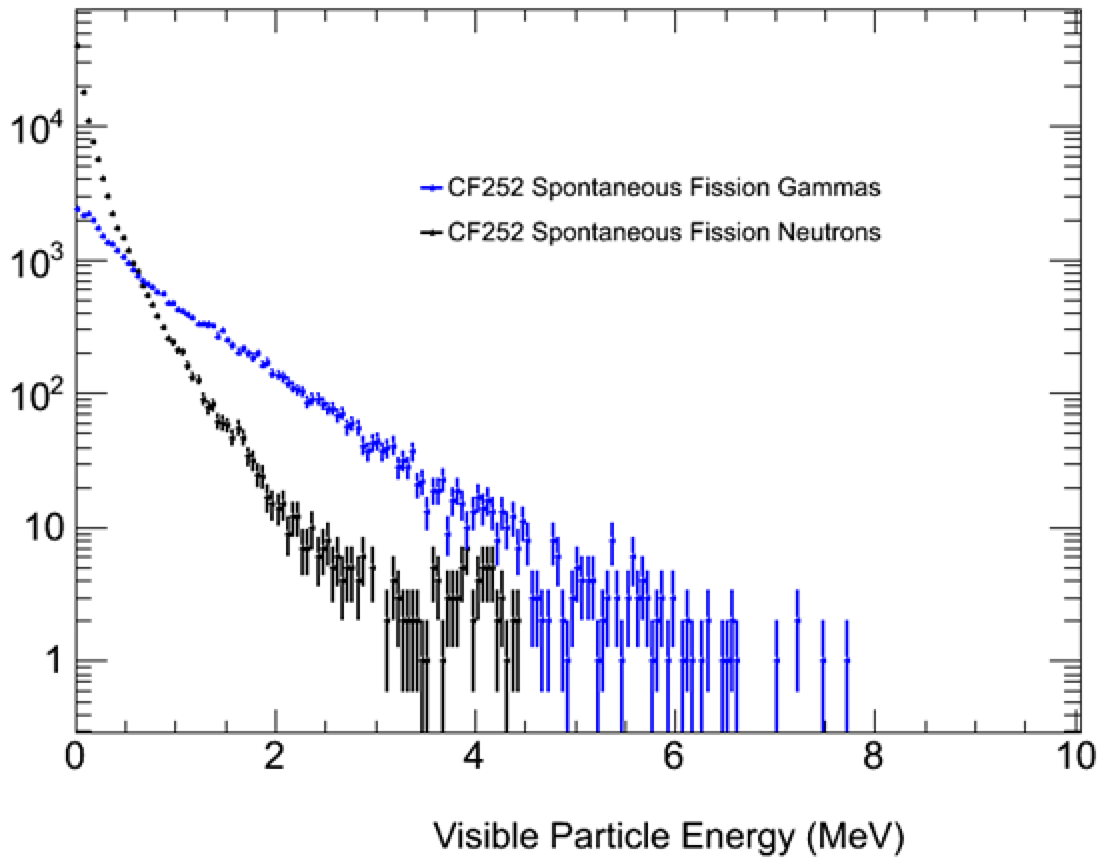
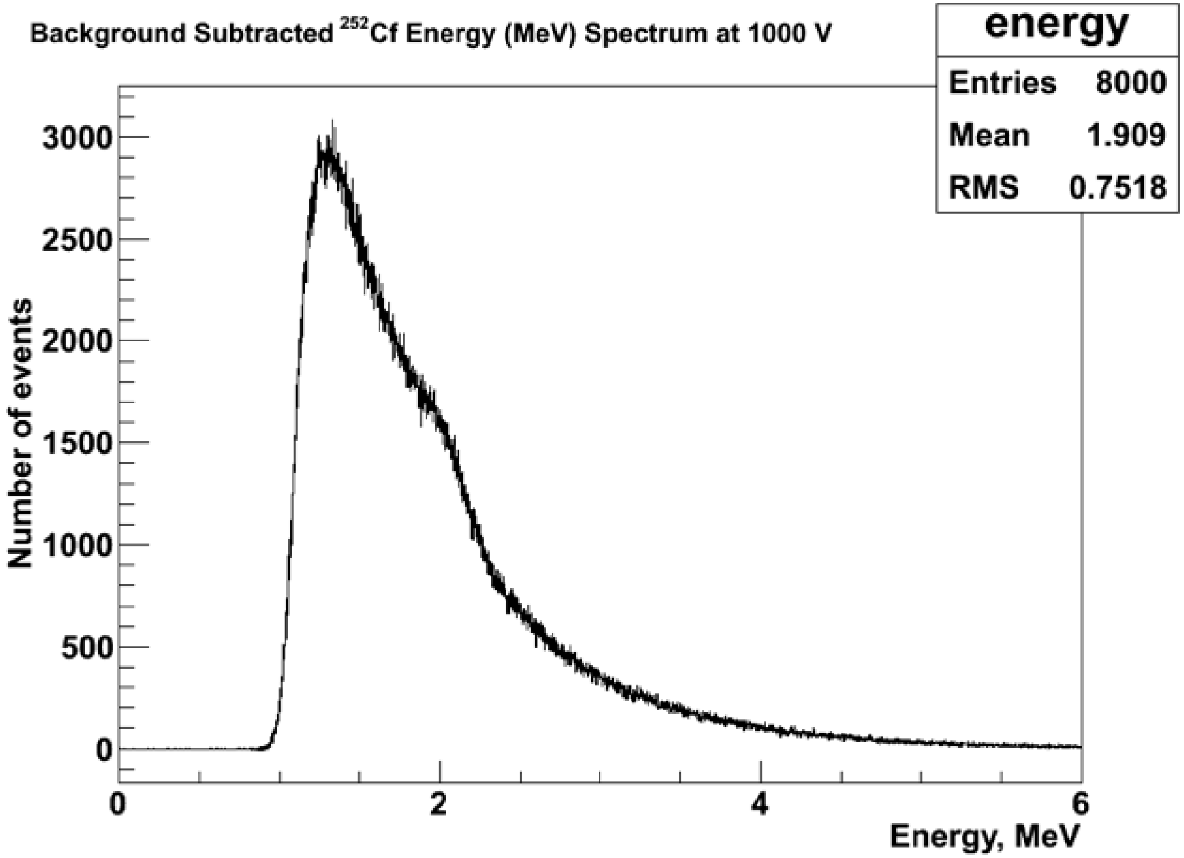
Results Part 2: CF-252 Deposited Energy



- Monte Carlo – therefore can remove neutron capture processes from the simulation entirely (not physical)
- No peak seen

Results Part 2: CF-252 Data



- Measured by UCL using scintillator
- Peak also seen at 2 MeV - as seen in MC?

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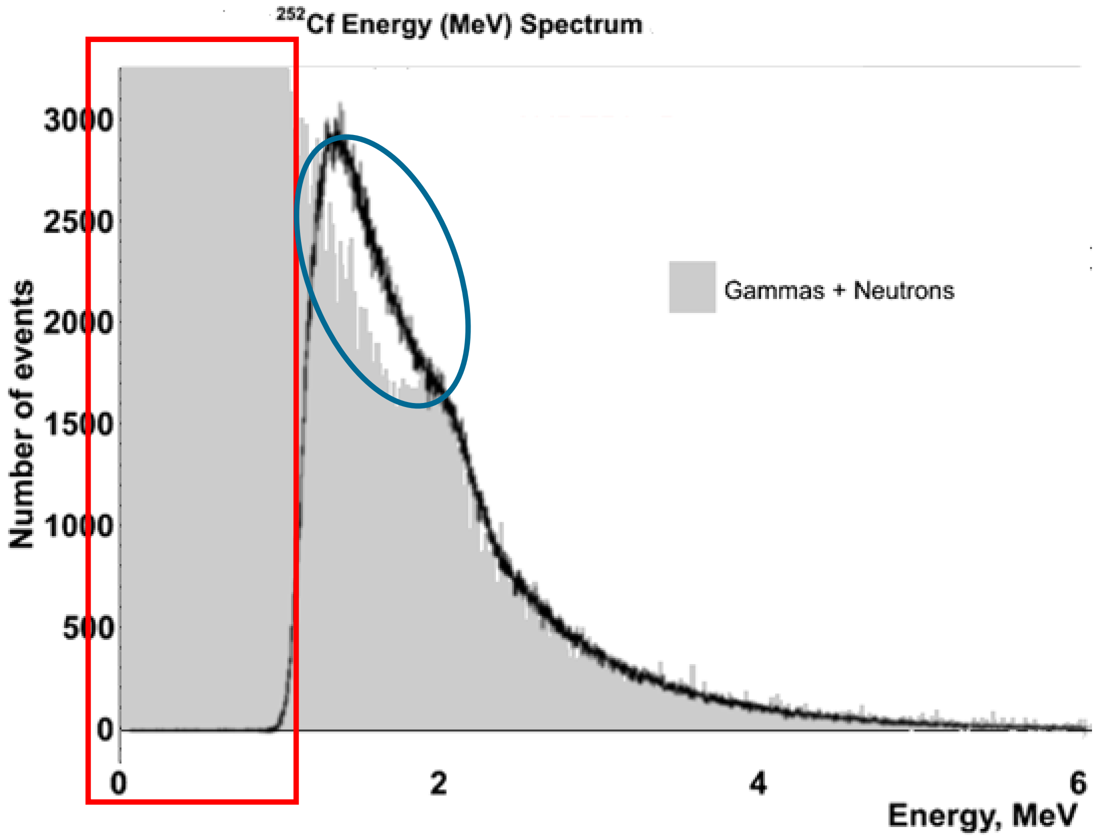
Results Part 2: CF-252 Data/MC Comparison



- Total energy deposited
- Shape match only (data black, MC grey)
- Deficit in MC events below 2 MeV
- Excess in MC events at lowest energies

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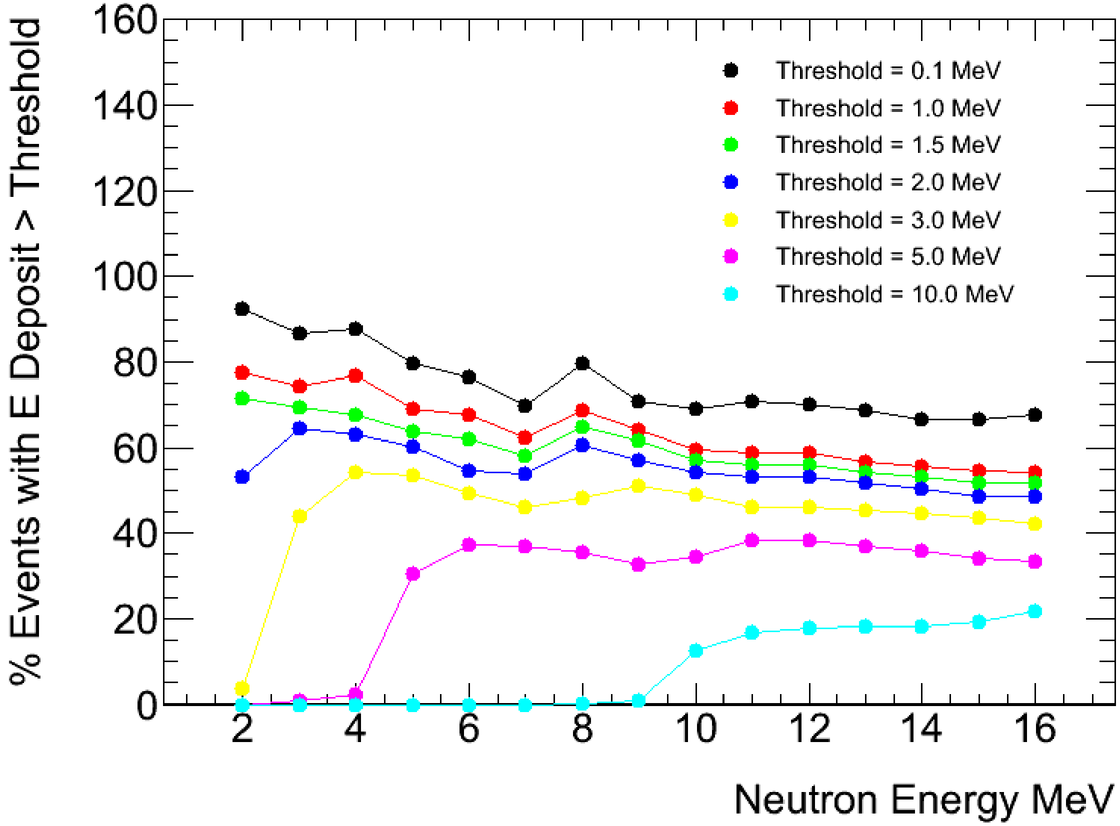
Results Part 2: Threshold Effects at Low Energy



- Detector has a minimum energy threshold for detection
- Causes a turn on curve that depends on the value of the threshold
- Statistical errors too small to view (8 MeV bump not due to statistics)

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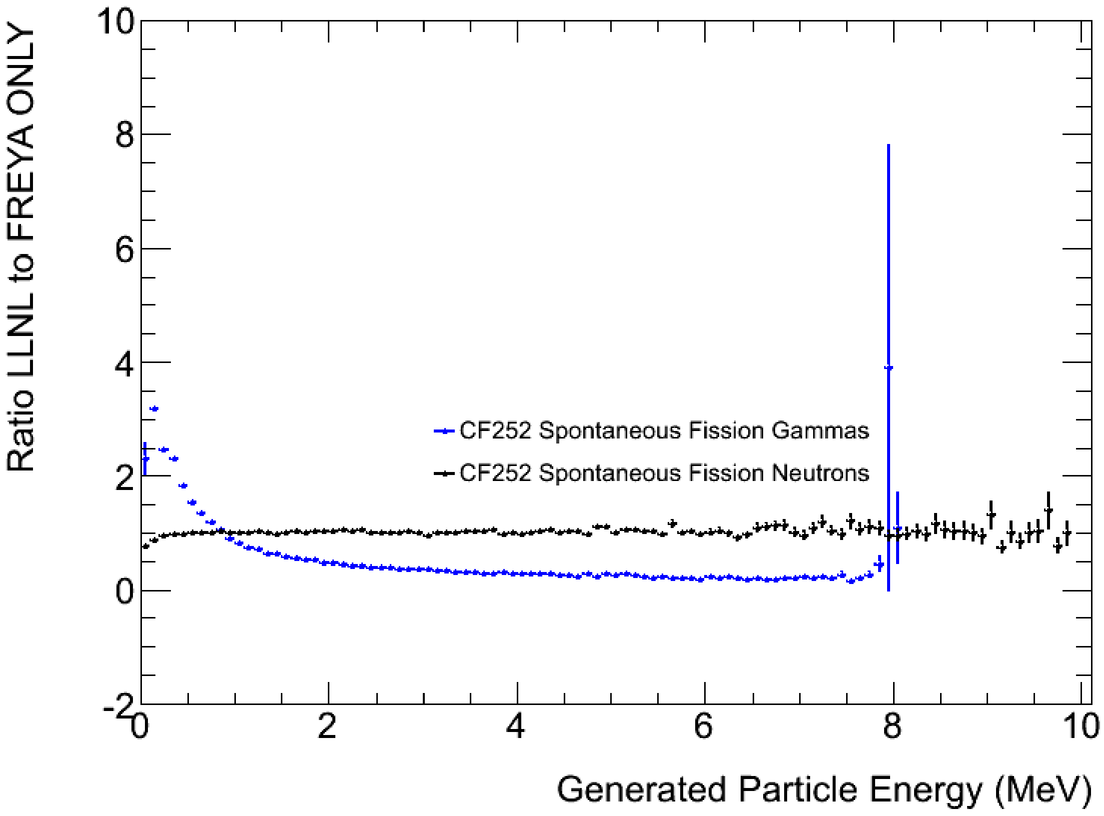
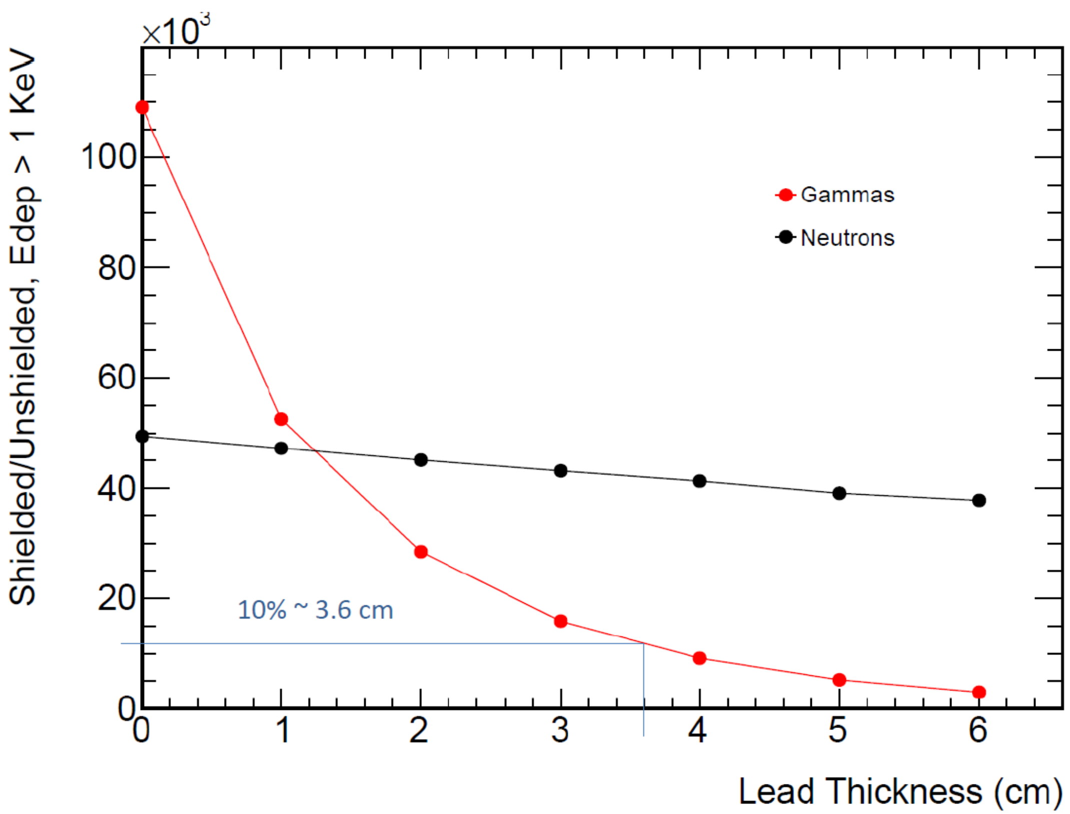
Results Part 2: Model Validation



- Lack of MC events below 2 MeV could be due to the generator modelling
- Comparison to Lawrence Livermore National Laboratory (LLNL) fission package
- Agreement in neutrons, disagreement in gammas

Results Part 2: Improve the Neutron Source



- Lead preferentially attenuates gammas
- Measurements with lead shielding between CF-252 and scintillator will mean a purer neutron source
- Reduce impact of uncertainty of gamma modelling

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Beam Line at Clatterbridge

- Ultimate goal – develop a neutron spectrometer
- Provide in situ measurements of neutron dose
- Optimise beam-line to reduce dose to patients and sensitive equipment

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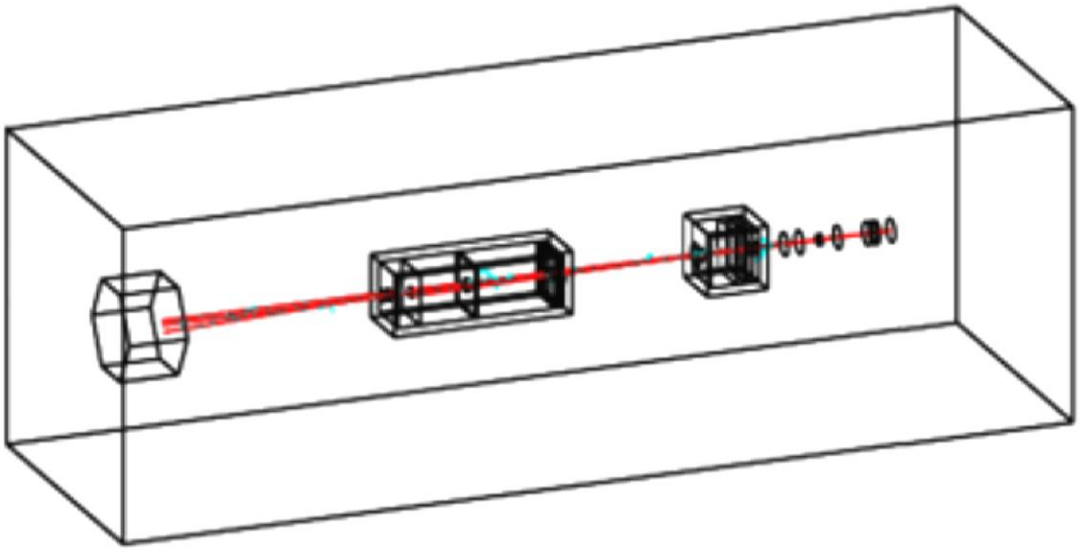
Results Part 3: Modelling The Beam Line in Geant4



- Core beam-line components modelled
- Concrete walls, ceiling and floor also added to recreate scatter conditions (not shown)
- 62.5 MeV protons (reduced to ~60 MeV by air scatter)
- 1,000,000 events

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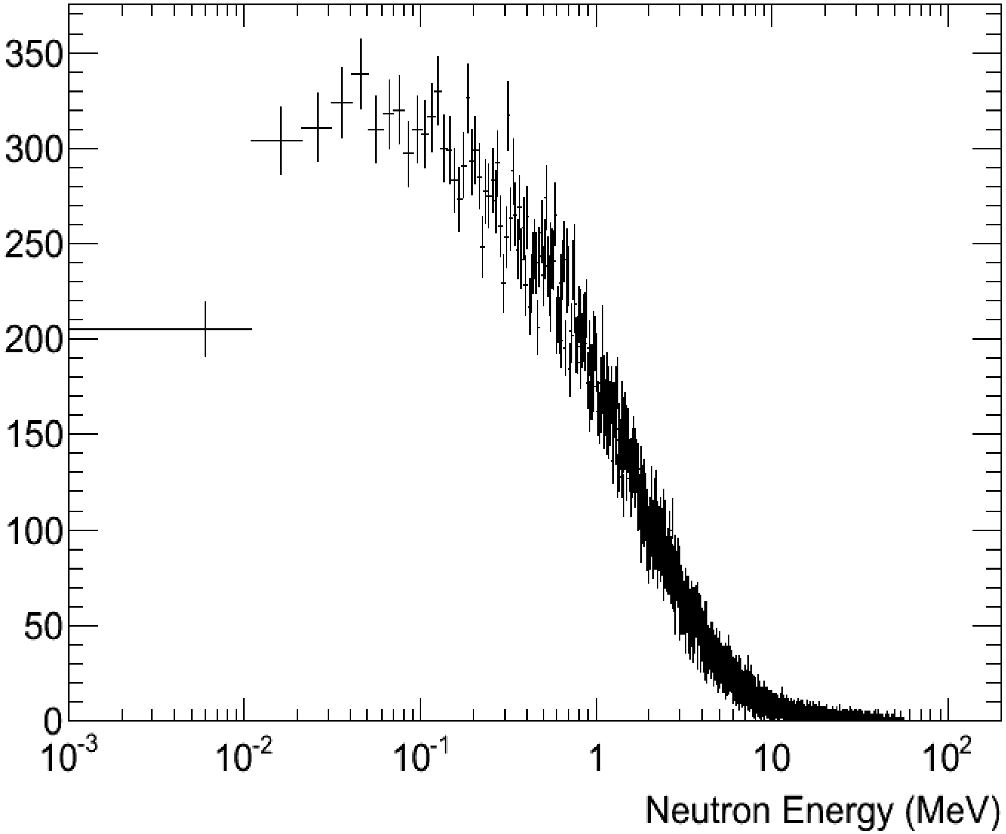
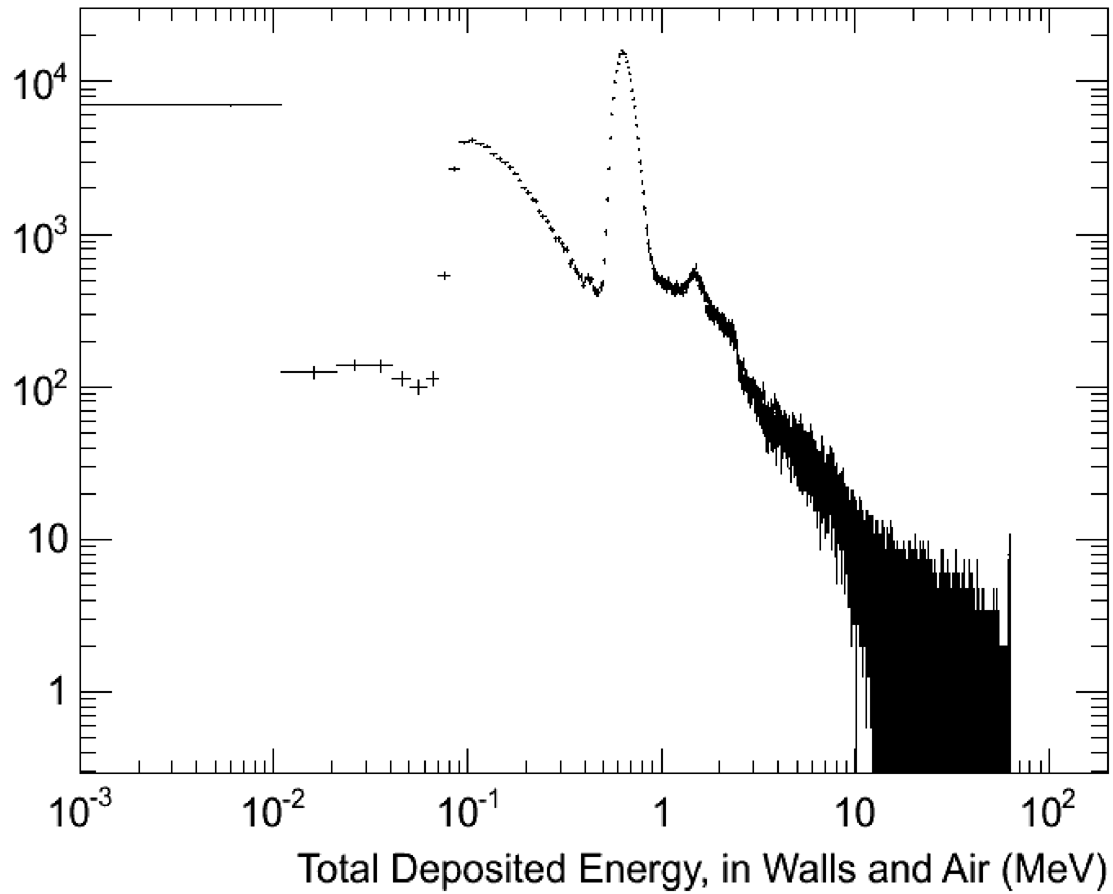
Results Part 3: Production of Neutrons in the Room



- Model (currently) shows about 7 neutrons produced per 100 protons in the room.
- As model complexity increases, more things to interact with will result in more neutrons
- These neutrons scatter widely

Results Part 3: Energy deposition in the Clatterbridge Treatment room



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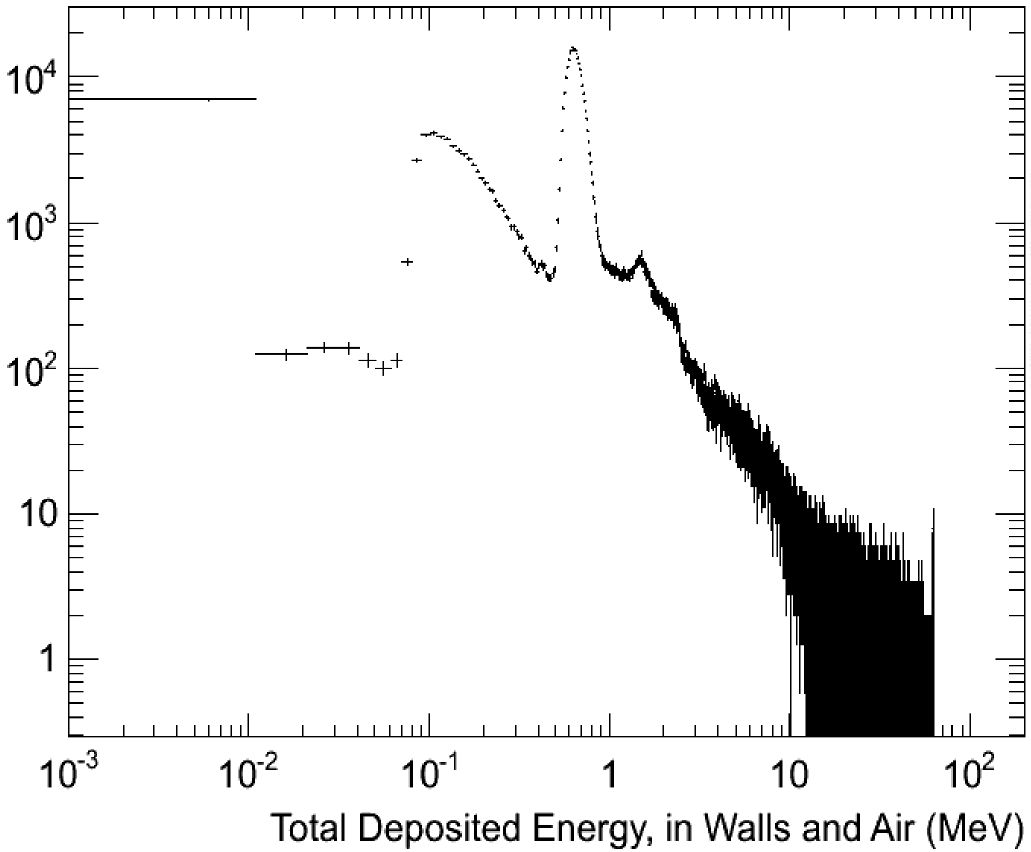

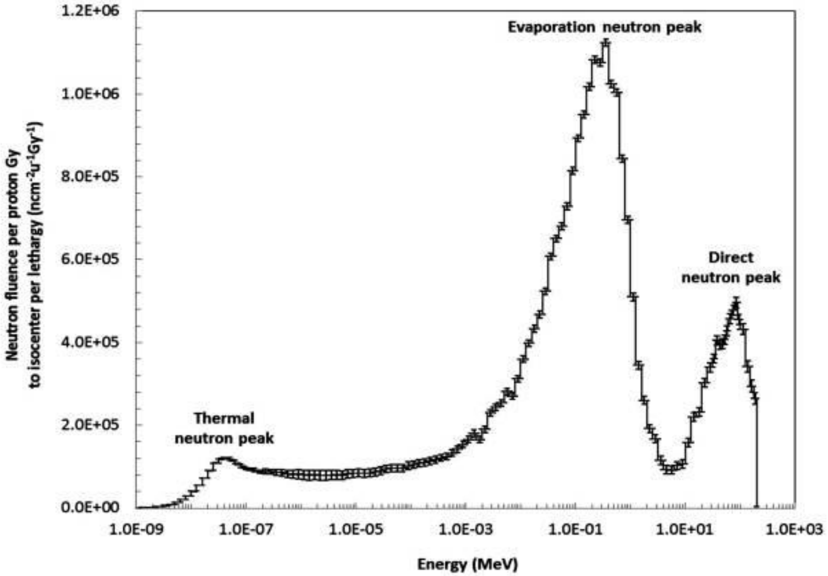

Source: Howell, Med Phys. 2014 Sep; 41(9): 092104

250 MeV Beam at 100cm from Isocentre.

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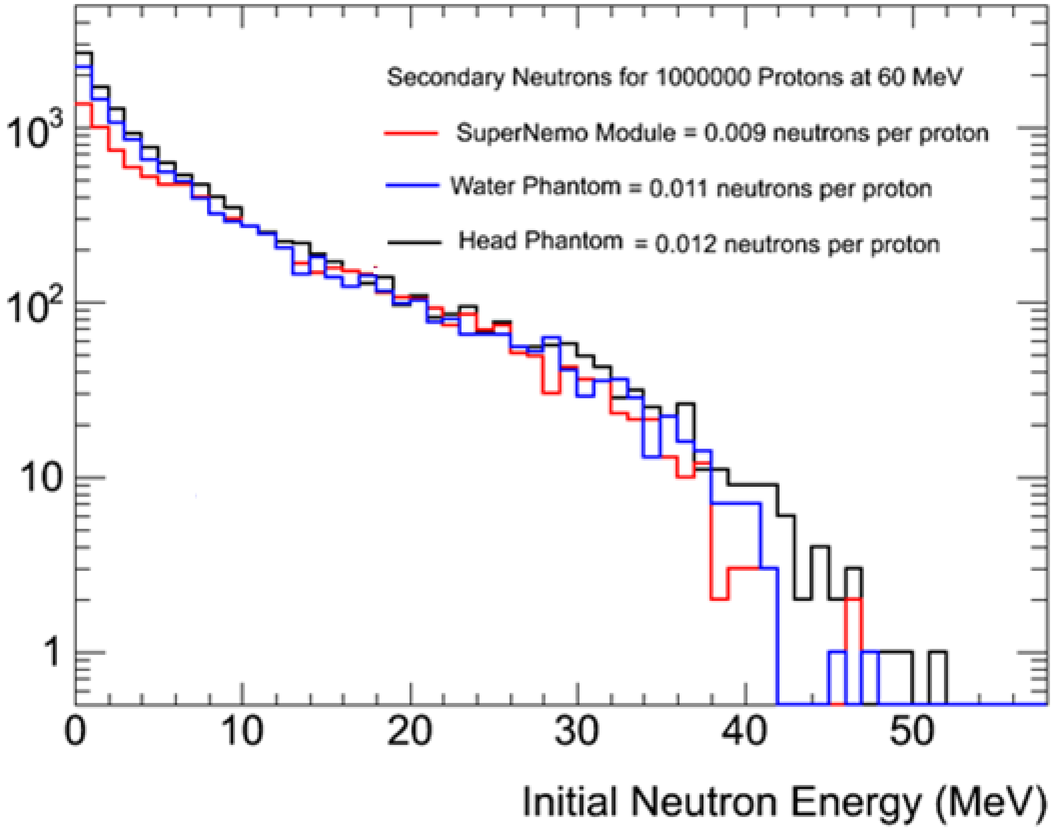
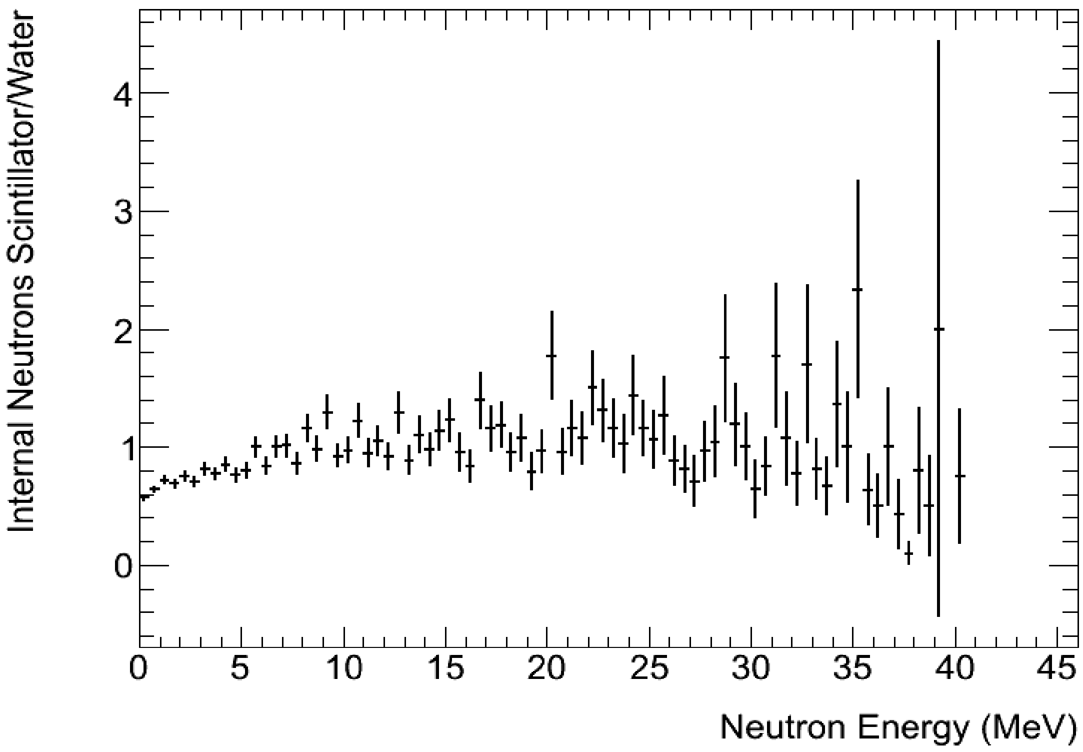
Results Part 3: Internal Neutron Production



- Neutrons are produced within the patient and detector and contribute to neutron dose ~ 1 neutron per 100 protons
- A correction may be required if patient dose calculations are performed using scintillator data

Results Part 3: Internal Neutron Production



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Summary and Future Work

- The response of the detector to neutrons has been modelled using Geant4 and compared to a CF-252 source
- The beam-line in Clatterbridge has been modelled and the neutron production within the room assessed
- Future plans:
  - CF-252 comparison with lead shielding
  - Dose deposition as a function of distance from beam-line
  - Perform test-beam measurements at Clatterbridge to validate beam-line model and detector simulation

Thanks for Listening!

Clatterbridge Beam-Line

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