Highlights in Low Energy Hadronic Physics

Geant4 Collaboration Meeting
27 September 2017

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Outline

- De-excitation and Precompound
- Low Energy Database Models
- Radioactive decay
- Nuclear Resonance Fluorescence
- Neutrino Physics

Common Developments for Pre-compound/De-excitation

- G4DeexPrecoParameters scheme introduced in 10.3 is extended
  - Printout of all important parameters values at initialisation
  - Modification of parameters allowed only at G4State_PreInit
  - New booleans added to allow disabling of de-excitation module

- Only one singleton class G4NuclearDataStore left with static data shared between all threads
  - No longer any thread local data

- Time and creator model information is propagated to G4HadronicProcess
  - Allowing proper checks of charge and energy conservation
    - Emission of Auger electrons breaks old checks

De-excitation Module for 10.4

- Evaporation/FermiBreakUp/Photon evaporation updated according to plan for 10.4
  - Data structure for gamma levels is finalized with G4PhotonEvaporation5.0

    Half the size of data in 10.3

    Laurent Desorgher produced data files

    Fixed several bug reports for 10.3 concerning radioactive decay and photon evaporation

    Optimized data structure: use double, float and integer with maximum compression of data
  - In all classes of the module excited energy of a fragment is taken from the DB directly without any conversion and not computed on-fly

    Providing reproducibility
  - Isomer production is enabled by default

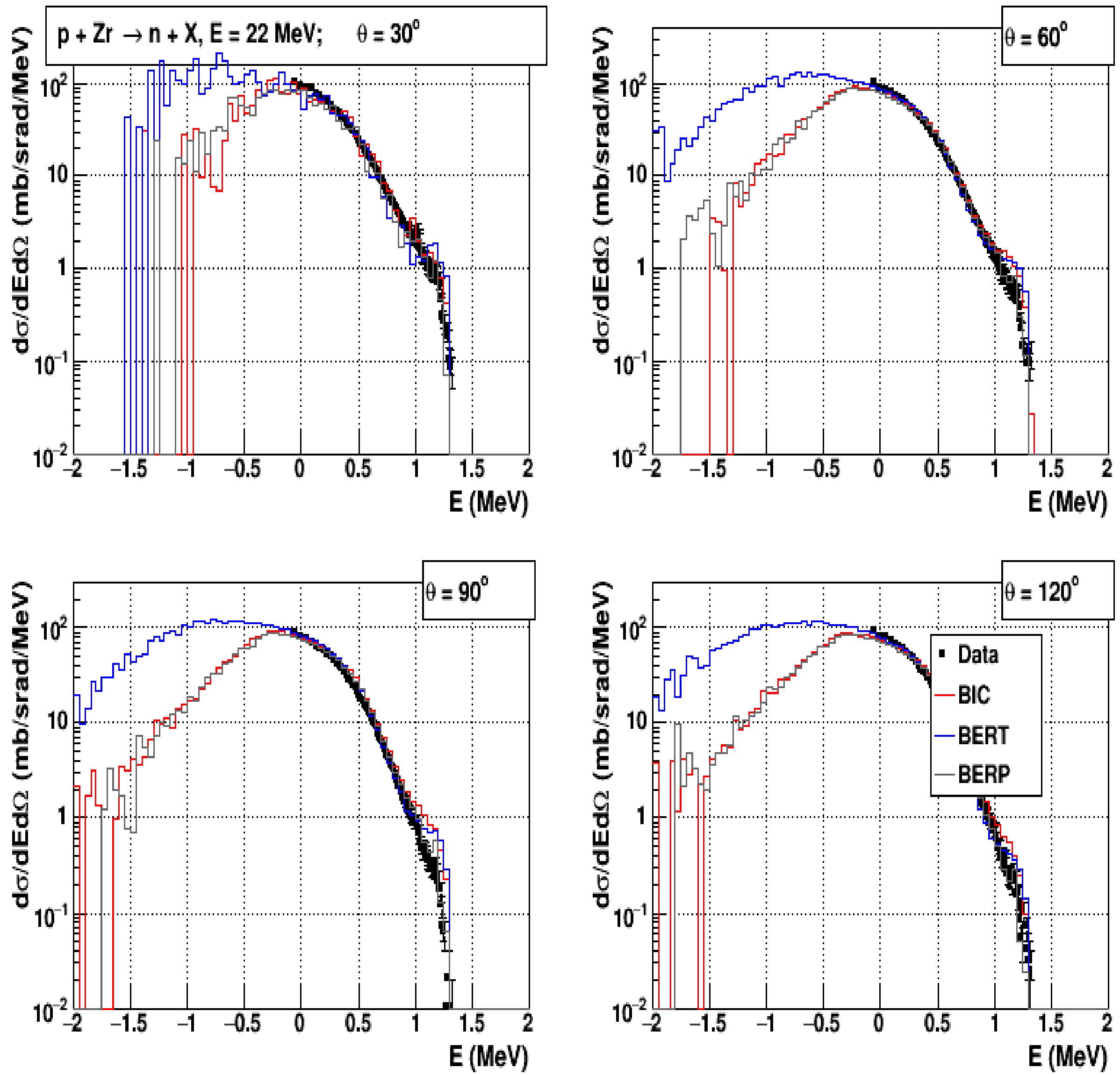
    Time limit is taken from G4NuclideTable providing full synkronisation between production and decay

De-excitation Module for 10.4

- Correlated gamma decay (Jason Detwiler, University of Washington)
  - Works for several important isotopes (Co60) but provides very long loops if applied in general
  - Triggers non-reproducibility and slow-down in radioactive decay chain sampling
  - Enabled by request or by G4RadiactiveDecayPhysics

    May be disabled by default also for radioactive decay if problems will not be fixed before 10.4

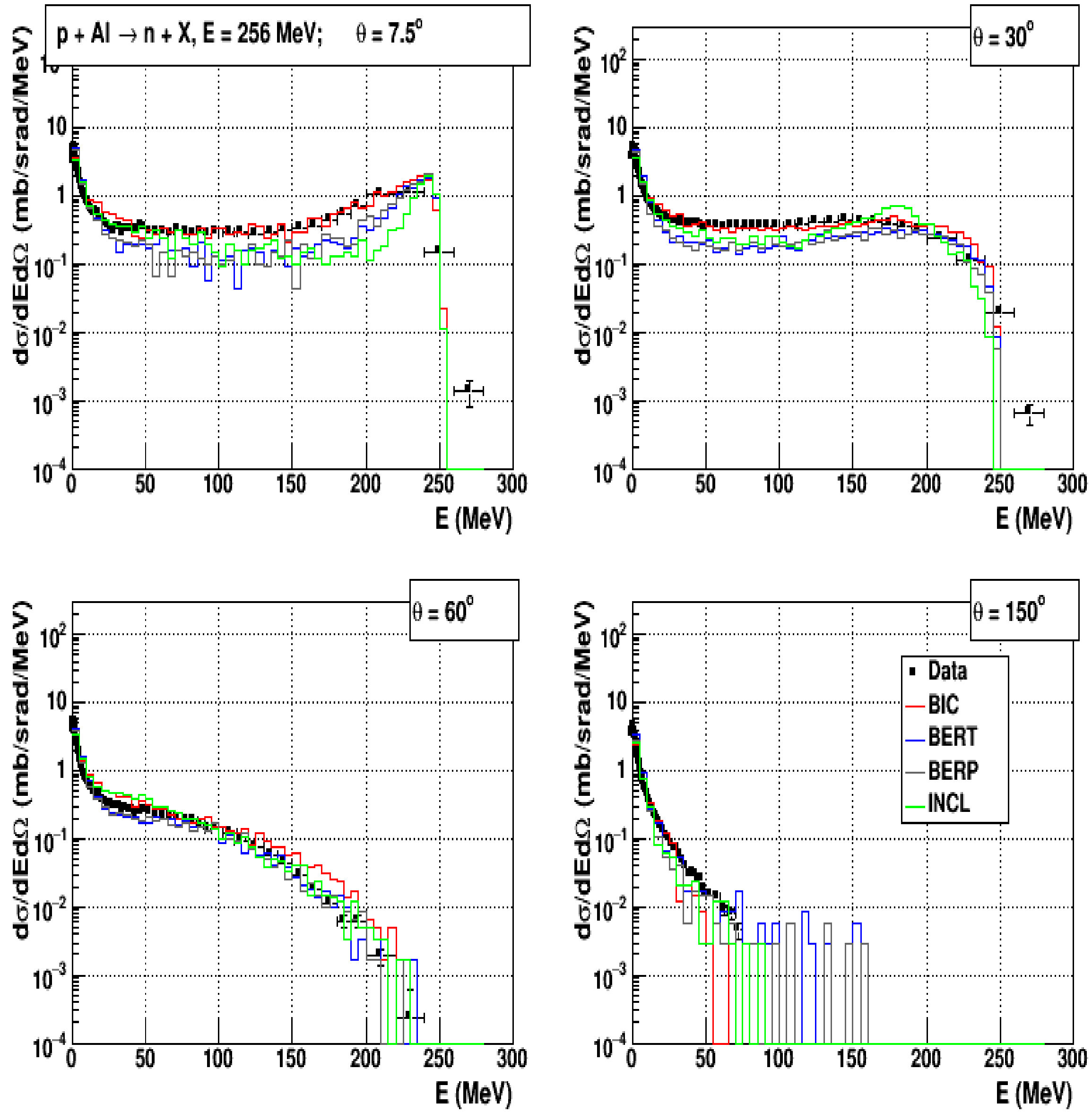
Double Differential Spectra of Neutrons for 22 MeV Proton Beam



The Binary cascade predicts more supressed low-energy part of the spectra than the Bertini cascade

There are non-ideal description of the end of the spectra, which means that cascades are not accurate in sampling of quasi-elastic scattering

Double Differential Spectra of Neutrons for 256 MeV Proton Beam



The Binary cascade predicts more accurately forward neutron spectra

The Bertini cascade is more accurate in the backward hemisphere

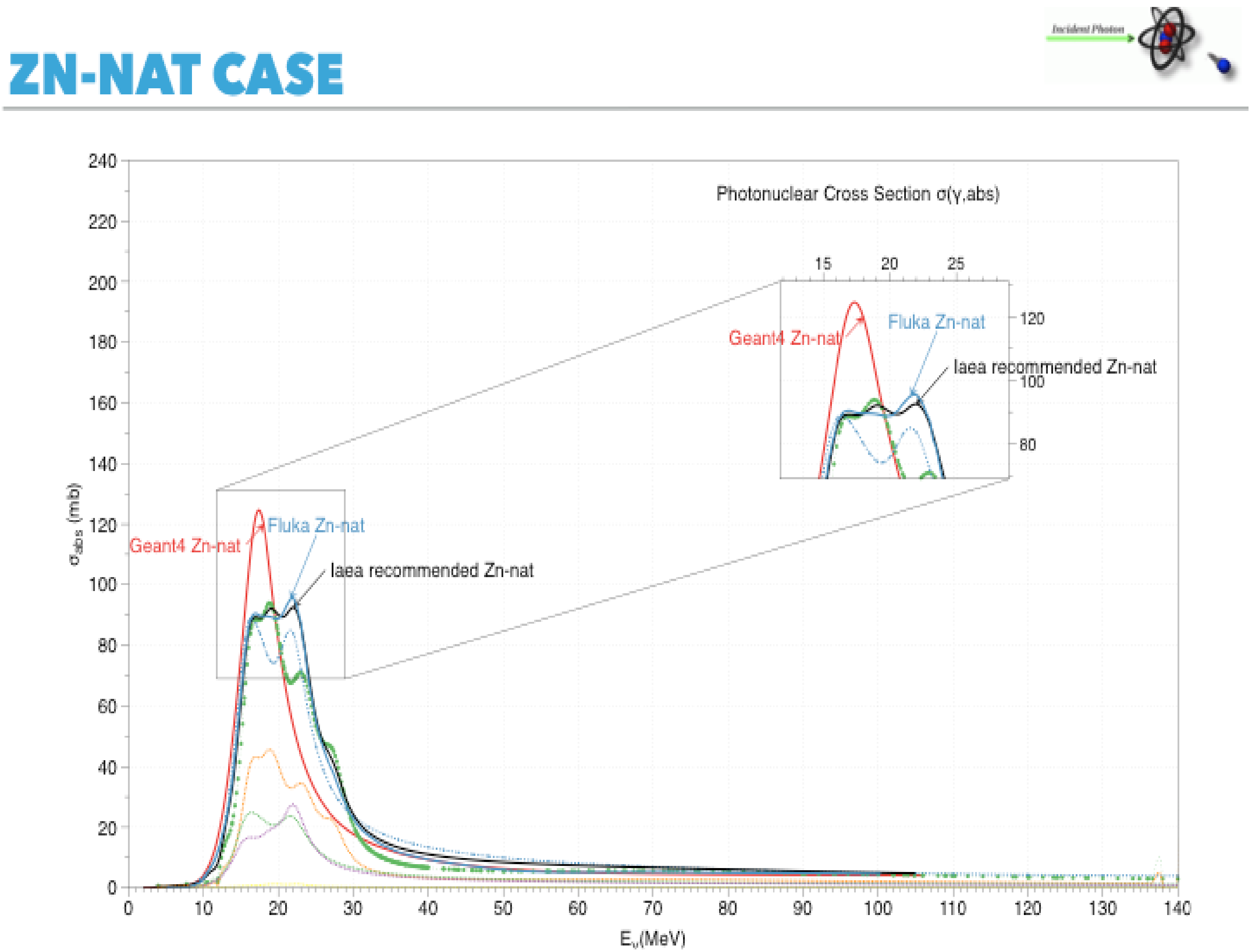
New Low Energy Photonuclear Model

- G4LENDorBertModel will use G4LEND models below 20 MeV
  - database has γ interaction information on isotopes from D to ^{241}Pu
  - for isotopes with no data, or for E_γ > 20 MeV → Bertini
  - cross sections also come from LEND, unless no data, then use G4PhotoNuclearCrossSection as we do now

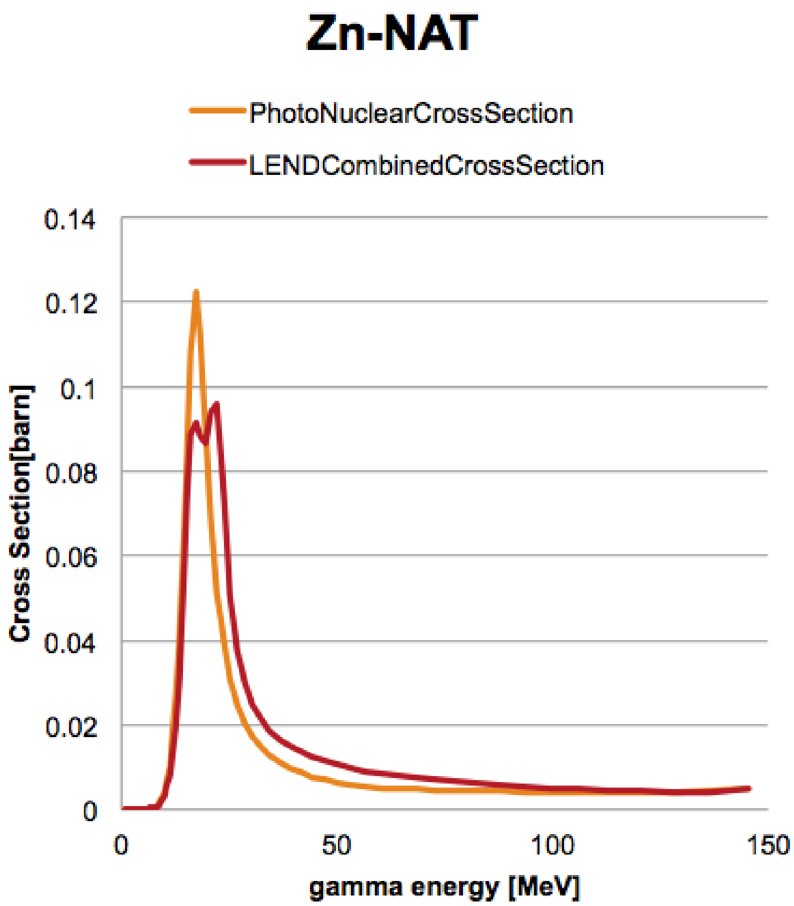
- G4LEND gamma models parallel the LEND neutron models:
  - fission, capture, inelastic, elastic
  - to simplify usage in physics lists, fission, capture, inelastic to be combined into one model, elastic in another

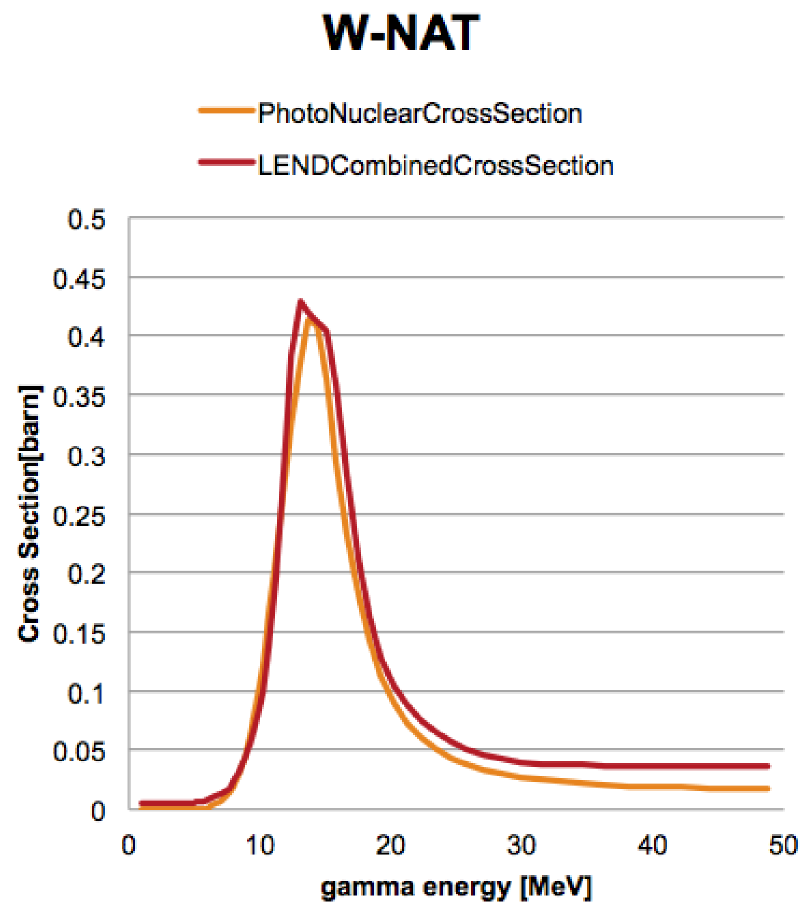
- Existing physics list, ShieldingLEND will be modified to include new model

Geant4/FLUKA Comparison, Quintieri et al. at SATIF 13

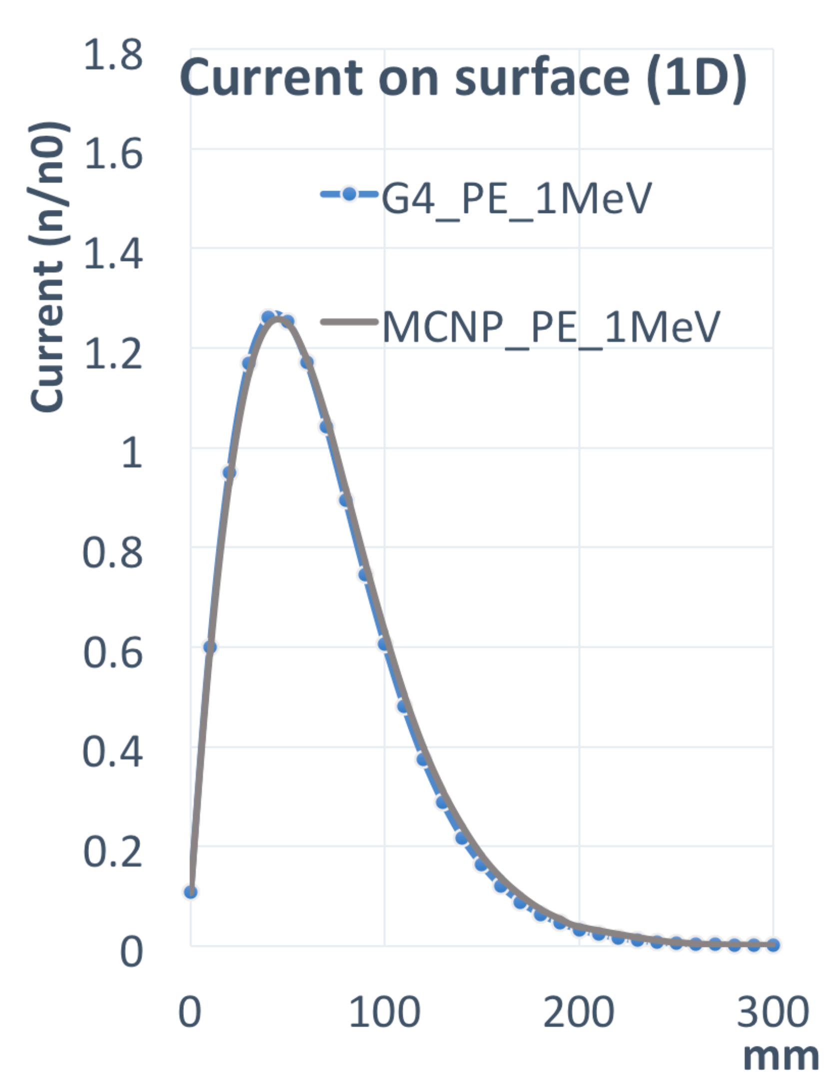


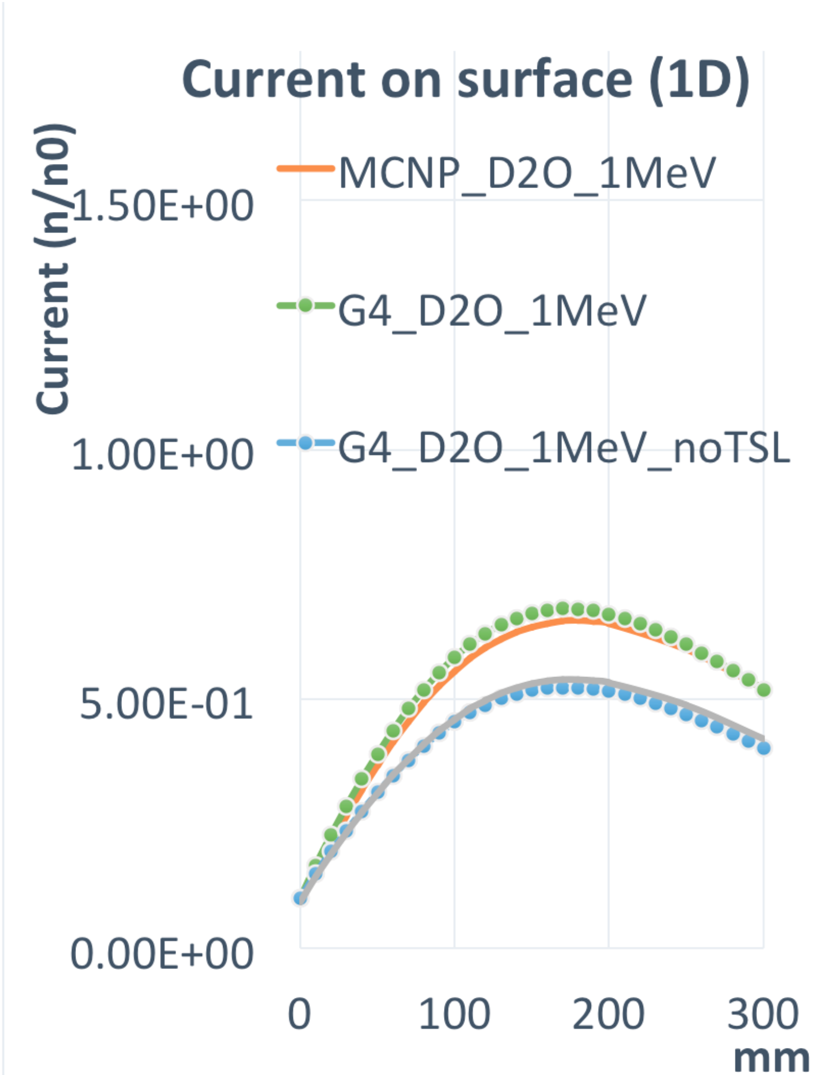
Cross Section Comparison, LEND vs. G4PhotoNuclearCrossSection





Thermal Neutron Scattering Validation
N.H. Tran @ CEA



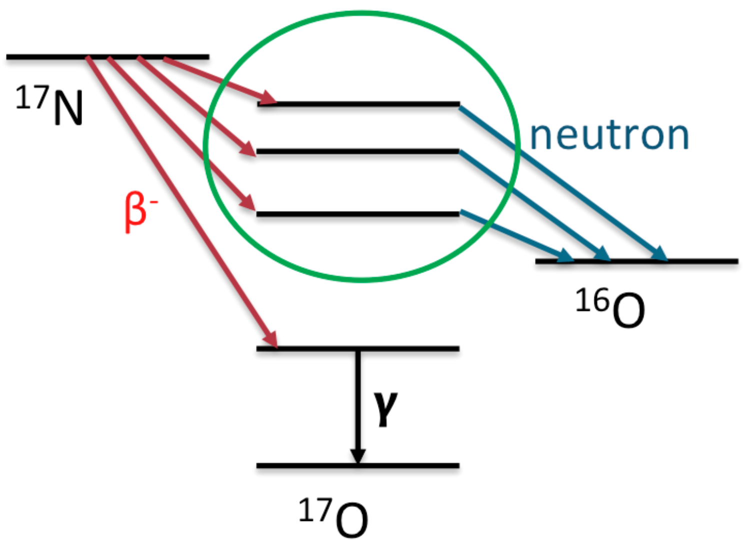


Radioactive Decay

- RDM mini-workshop held at CERN in April 2017
- Highlights
    - beta-delayed particle emission works for transitions to discrete levels
    - agreed to refactor RDM code into separate analogue and variance reduction models
    - reduction in number of half-life limits used in code
    - RDM and IT code refactored to include correlated gamma emission
    - photon evaporation and radioactive decay databases now consistent in format and notation (both taken from ENSDF)
    - new example: rdecay03

Discrete beta neutron/proton delayed decay in G4RADECAY data

Example decay of ^{17}N



- Neutron and proton decay channels already implemented in GEANT4 by Pico
- Add neutron decay in the data for excited states of ^{17}O, ^{16}N
- Add proton decay in the data for excited states of ^{13}N

Radioactive Decay

- New radioactive decay models
  - G4RadioactiveDecayBase (all variance reduction code stripped out)
  - G4Radioactivation (derived from G4RadioactiveDecayBase, only VR code kept)
  - Original class G4RadioactiveDecay kept
- Interface changes
  - Refactored code contains changes that would break user code – must wait until major release to replace G4RadioactiveDecay
  - two user commands will become obsolete
    - fBeta
    - analogueMC

Multipolarity and mixing ratio

Two cases of gamma transition in ENSDF

- Single multipolarity for example E_1
- Mixed multipolarity for example E_1+M_2

  mixing ratio = δ, fraction E_1 $1/(1+\delta^2)$, fraction M_2 $\delta^2/(1+\delta^2)$

In GEANT4 database single and mixed multipolarities are defined by integers

Multipolarities E1,M1,E2,M2,E3 -> 2,3,4,5,6,7
Monopole transition E0 -> 1
Mixed multipolarity X+Y defined by 100*Nx+Ny
example M1+E2 is defined by 304

```
6  -  1402.71        0   4.0   2
   3   559.58       61     4       0  0.00664   0.8499   0.09629  ...
   2   574.18      100   304    1.9   0.0072   0.8524   0.09741  ...
```

multipolarity (↑ 304) mixing ratio (↖ 1.9)

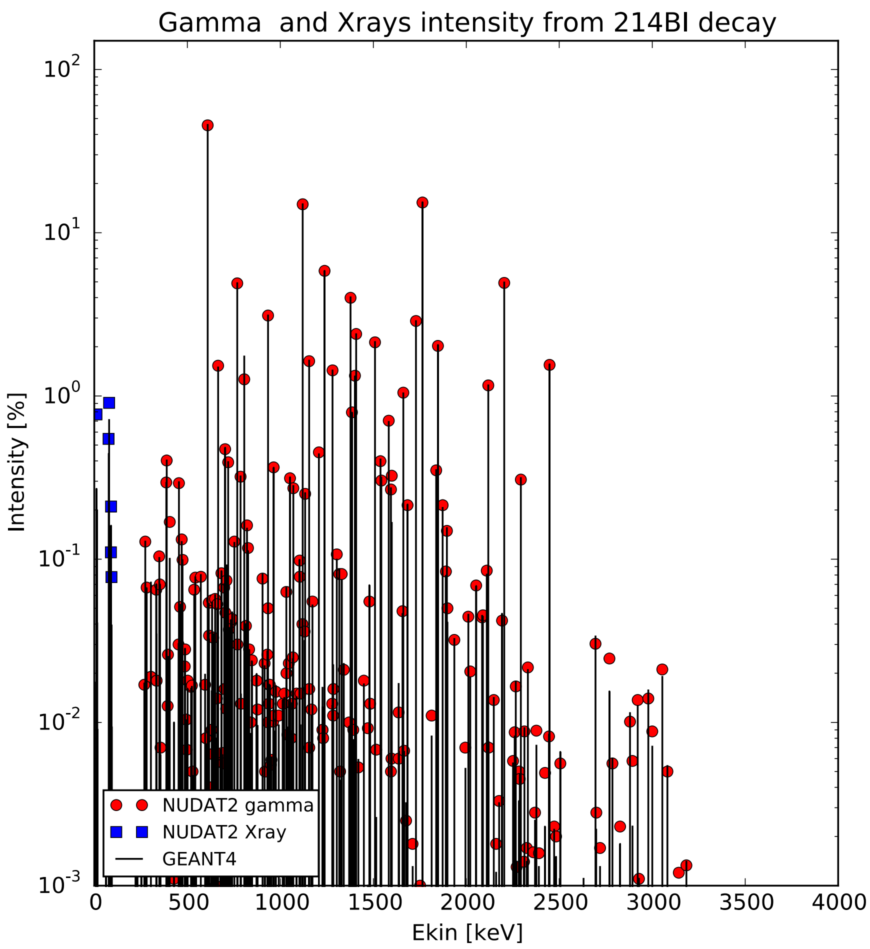
Geant4 databases for radioactive decay

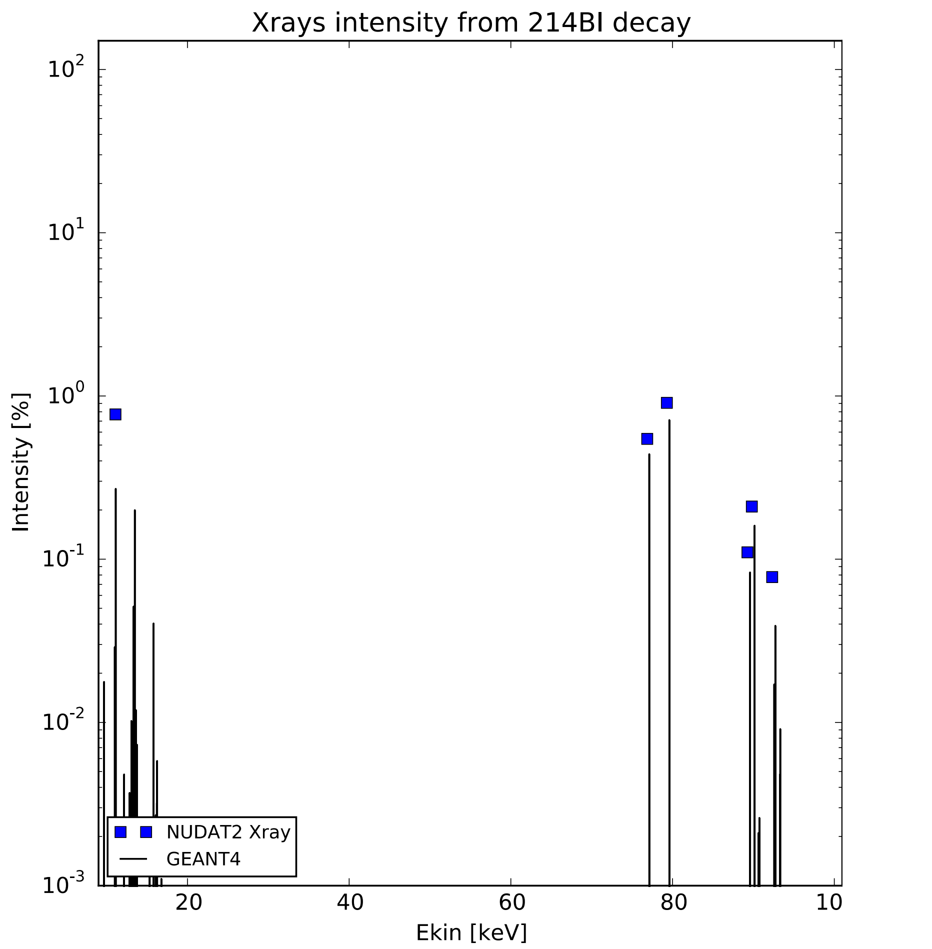
RadioactiveDecay5.1.1
Data for beta, alpha, EC, neutron, proton decay

Photonevaporation4.3.3/5.0.2
Data for de-excitation of excited nuclear level by gamma and internal conversion

ENDFSTATE2.2
Defined all ground states and excited levels with non zero lifetime

Validation Example: Bi214





Radioactive Decay Tasks

- Examine possibility of using matrix algebra to implement time evolution of Bateman equations

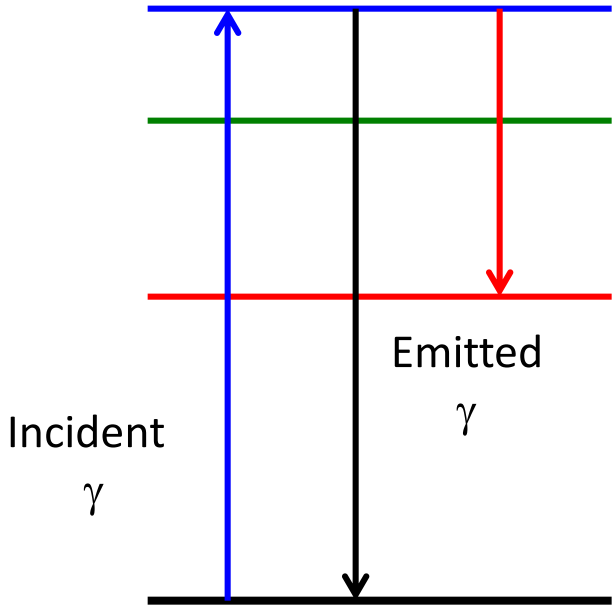
- Complete beta-delayed particle emission to continuum
- Investigate use of Kibedi model of atomic deexcitation

- Validate new correlated gamma code
- New examples, including correlated gammas

- Decide what to do with floating to non-floating transitions

G4NRF:
Extending Photonuclear to Lower Energies

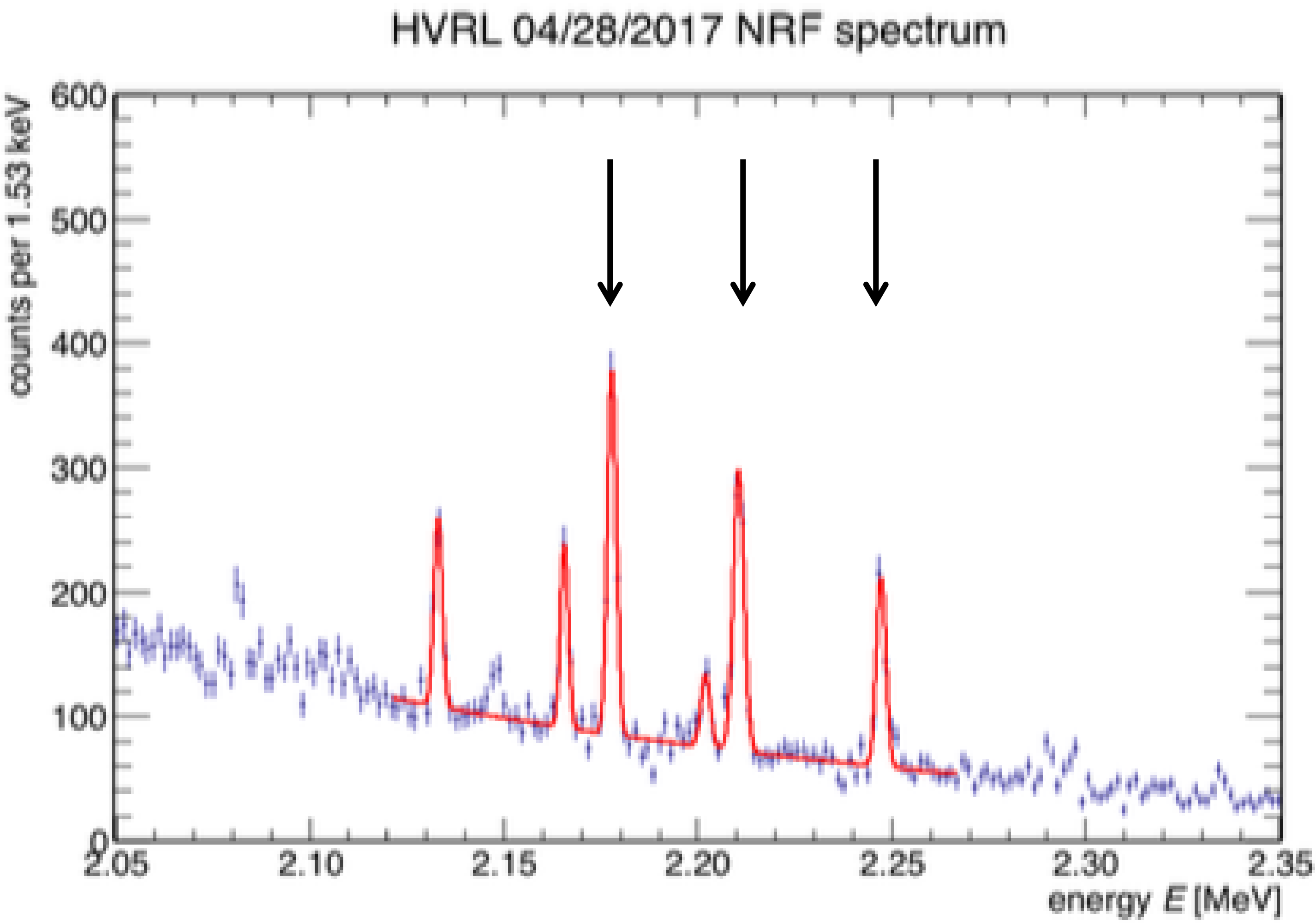
Nuclear Resonance Fluorescence



G4NRF developed by Jayson Vavrek (MIT)

- 10 keV < E_γ < ~10 MeV
- sharp lines (~few eV or less)
- uses mostly ENSDF, but also needs extra DB
- planned for inclusion next year
- many applications

^{238}U NRF Spectrum from Bremsstrahlung Gammas (endpoint 2.5 MeV)



G4NRF Thin Target Validation

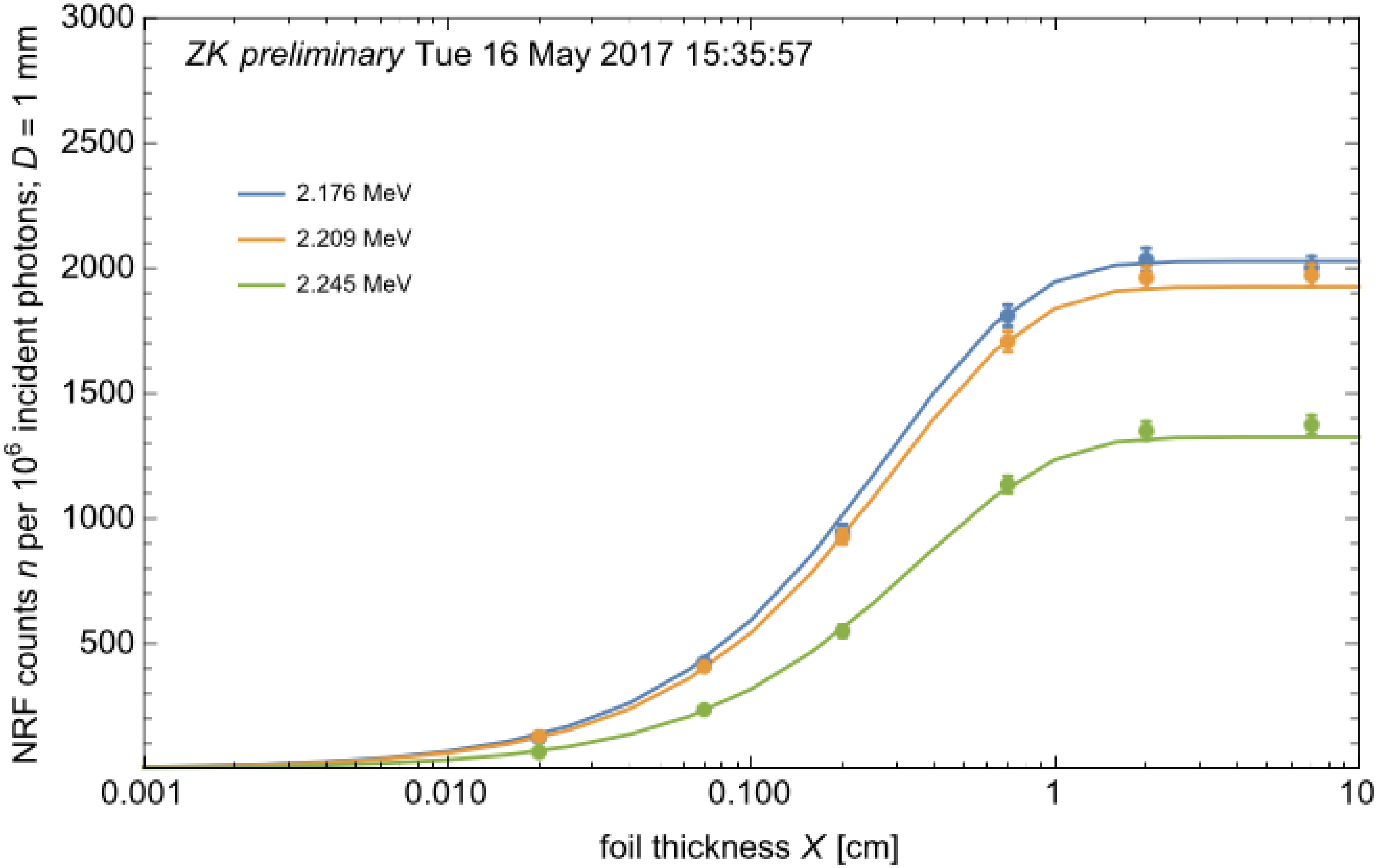
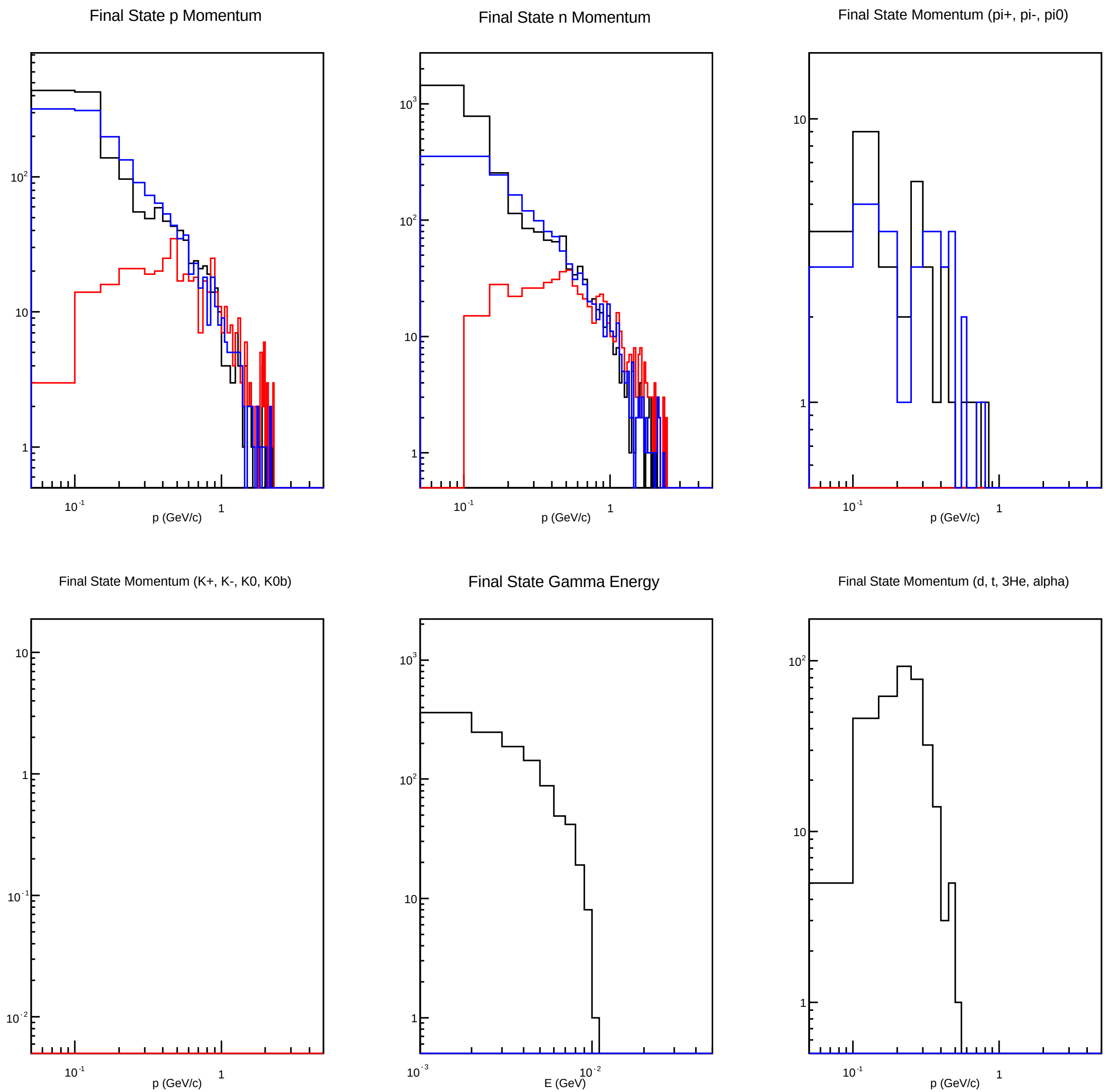


Figure 3: Validation of G4NRF in U-238 with a thin (1 mm) target.

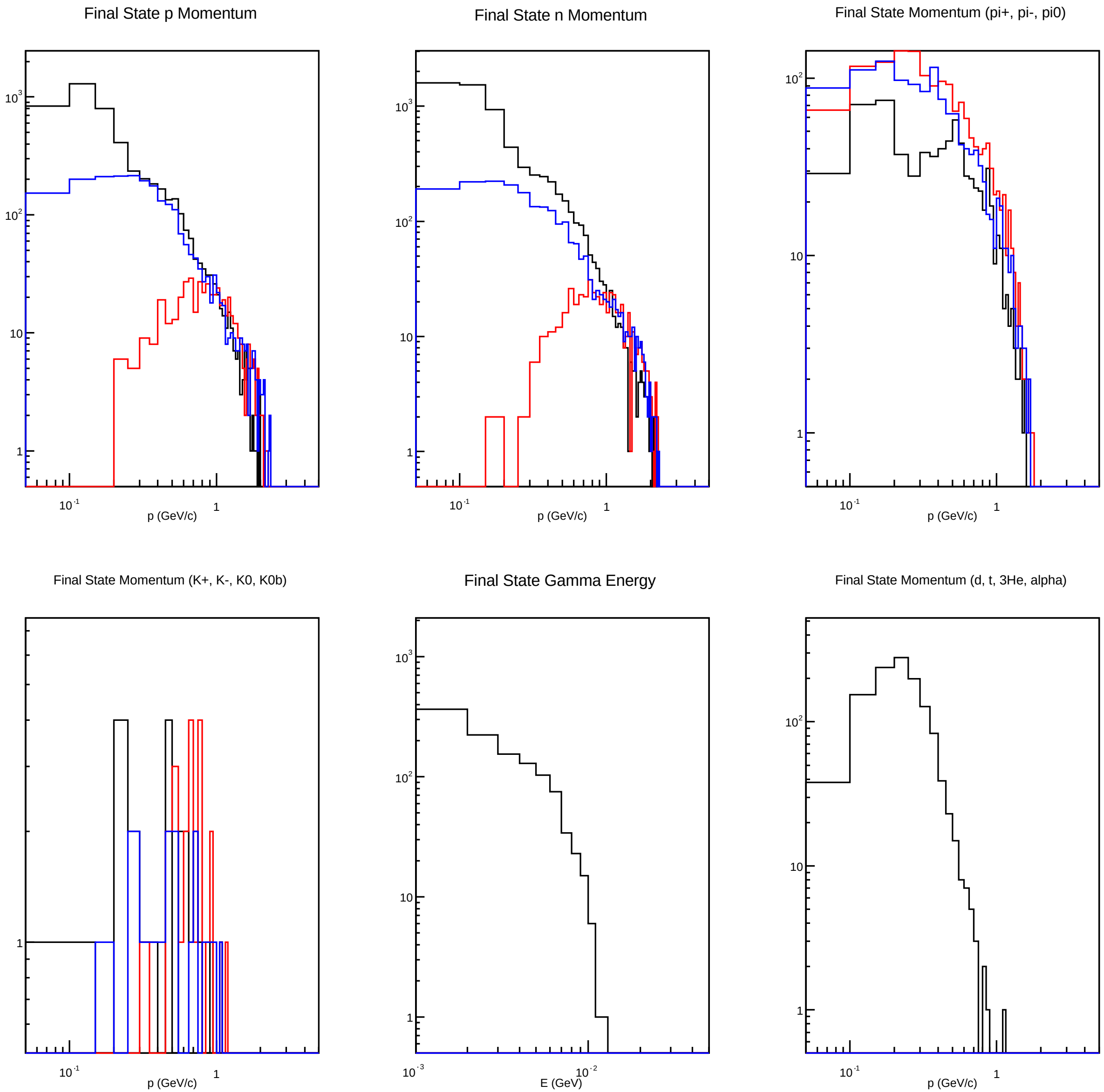
Neutrino Scattering

- First step: Geant4-to-GENIE interface
  - use Geant4 Bertini cascade to do final state interactions in nucleus after GENIE neutrino vertex is generated
  - complete, committed to GENIE svn
  - validation underway
- Next step: GENIE-to-Geant4
  - use GENIE neutrino generators to initiate neutrino interactions in Geant4
  - need wrapper models to have GENIE models treated as Geant4 models
  - some native Geant4 neutrino cross section classes already exist (V. Grichine)

Neutrino Scattering: NCEL (black: Bertini, blue: GENIE)



Neutrino Scattering: DIS (black: Bertini, Blue: GENIE)



Conclusions

- Several model extensions ready for 10.4
  - correlated gamma emission, radioactive decay extensions
- New models getting close
  - G4LEND-based photonuclear model
  - Neutrino scattering interface
  - Nuclear Resonance Fluorescence