Hadronic Physics III

Geant4 School at IFIN-HH, Bucharest

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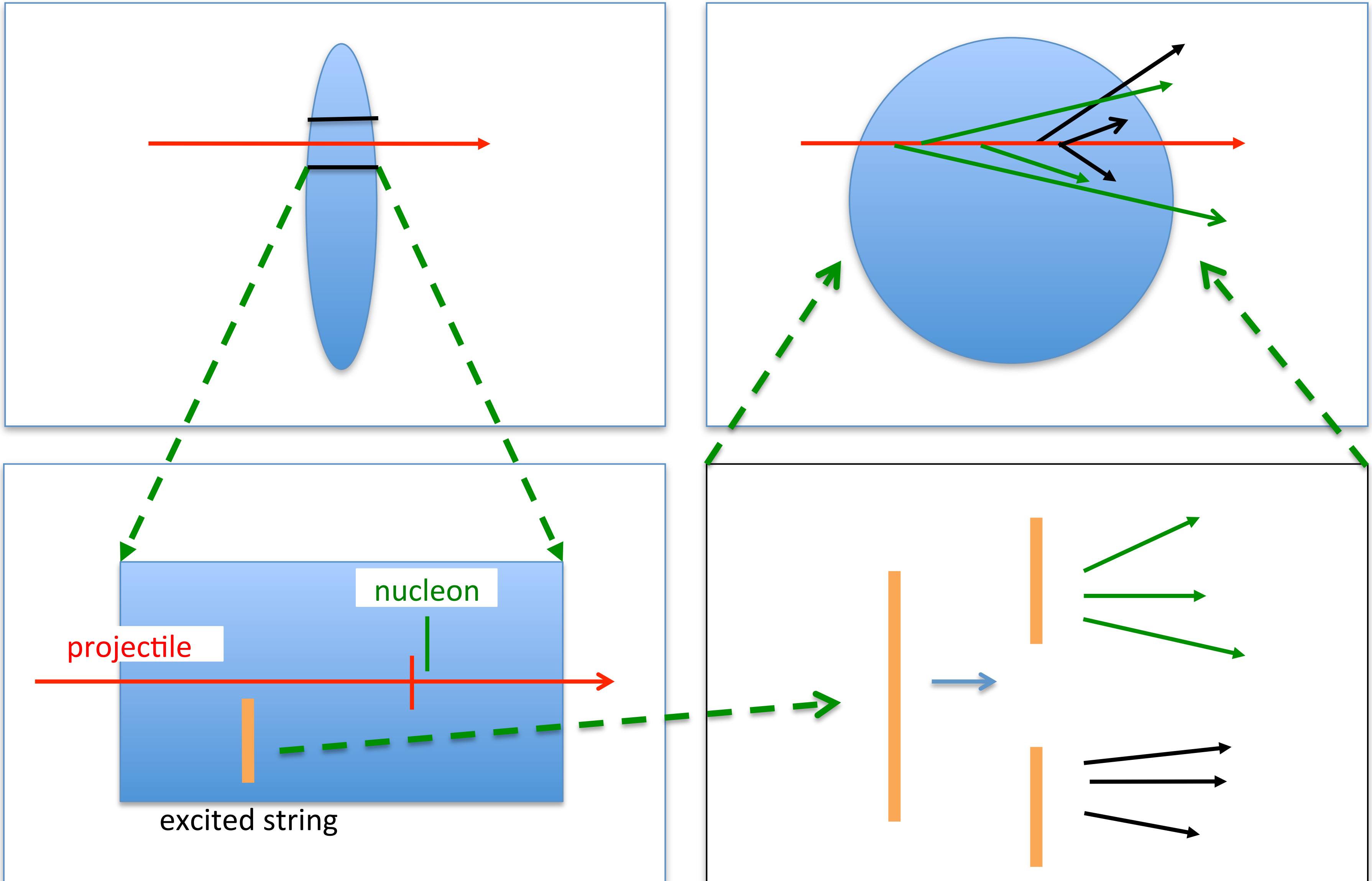
Outline

- QCD string models
- Gamma- and lepto-nuclear models
- Capture, Stopping and Fission models
- Radioactive decay

High Energy Nuclear Interaction



How the String Model Works (FTF Model)

- Lorentz contraction turns nucleus into pancake

- All nucleons within 1 fm of path of incident hadron are possible targets

- Excited nucleons along path collide with neighbors
  - n + n → nΔ, NN, ΔΔ, NΔ, …
  - essentially a quark-level cascade in vicinity of path → Reggeon cascade
- All hadrons treated as QCD strings
  - projectile is quark-antiquark pair or quark-diquark pair
  - target nucleons are quark-diquark pairs

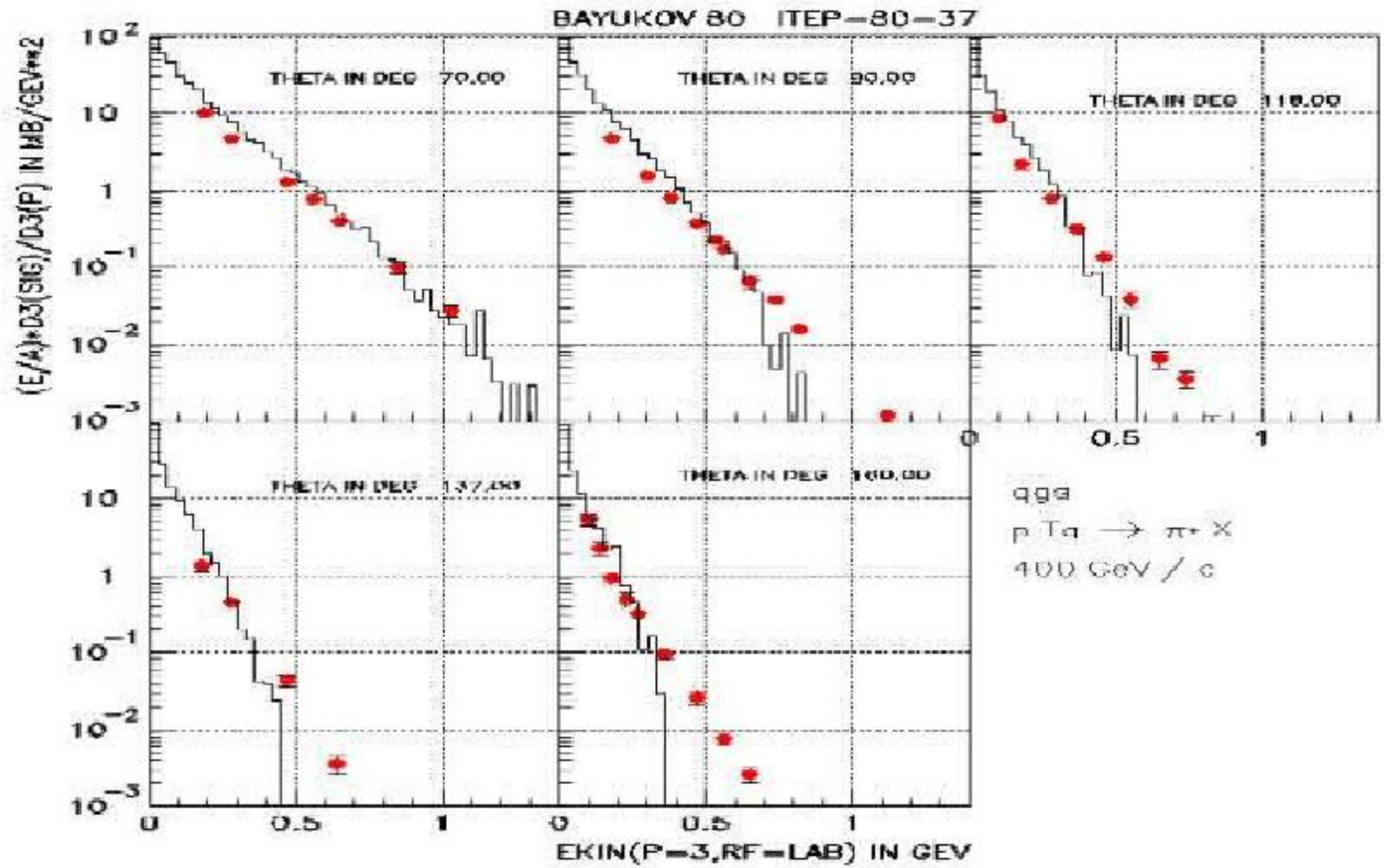
How the String Model Works (FTF Model)

- Hadron excitation is represented by stretched string
  - string is set of QCD color lines connecting the quarks
- When string is stretched beyond a certain point it breaks
  - replaced by two shorter strings with newly created quarks, anti-quarks on each side of the break
- High energy strings then decay into hadrons according to fragmentation functions
  - fragmentation functions are theoretical distributions fitted to experiment
- Resulting hadrons can then interact with nucleus in a traditional cascade

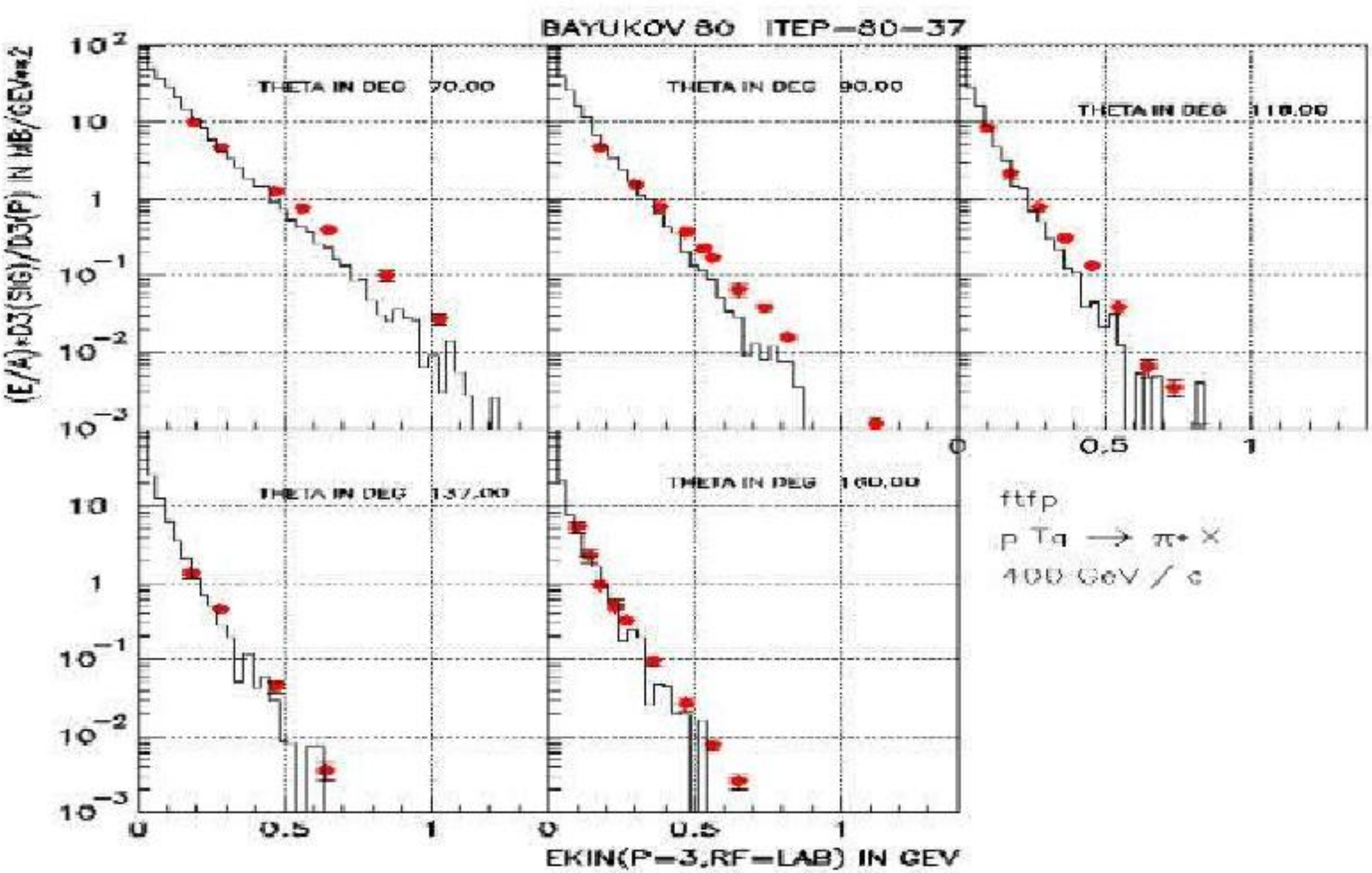
Two QCD String Models Available

- Fritiof (FTF) valid for
  - p, n, π, K, Λ, Σ, Ω from 3 GeV to ~TeV
  - anti-proton, anti-neutron, anti-hyperons at all energies
  - anti-d, anti-t, anti-^{3}He, anti-α with momenta between 150 MeV/nucleon and 2 GeV/nucleon
- Quark-Gluon String (QGS) valid for
  - p, n, π, K from 15 GeV to ~TeV
- Both models handle:
  - building 3-D model of nucleus from individual nucleons
  - splitting nucleons into quarks and di-quarks
  - formation and excitation of QCD strings
  - string fragmentation and hadronization

QGS Validation



FTF Validation



Gamma- and Lepto-nuclear Processes

- Geant4 models which are neither exclusively electromagnetic nor hadronic
  - gamma-nuclear
  - electro-nuclear
  - muon-nuclear

- Geant4 processes available:
  - G4PhotoNuclearProcess (implemented by two models)
  - G4ElectronNuclearProcess (implemented by one model)
  - G4PositronNuclearProcess (implemented by one model)
  - G4MuonNuclearProcess (implemented by two models)

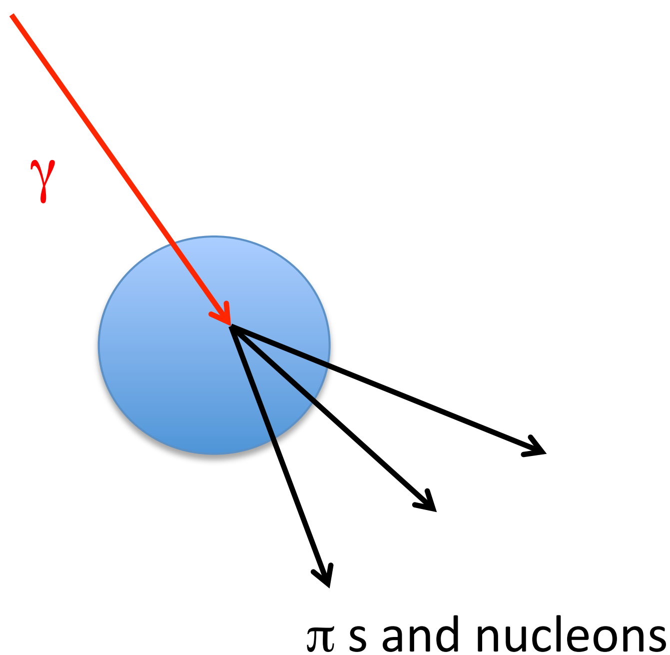
Gamma- and Lepto-nuclear Processes

- Gammas interact directly with the nucleus
  - at low energies they are absorbed and excite the nucleus as a whole
  - at high energies they act like hadrons (pion, rho, etc.) and form resonances with protons and neutrons

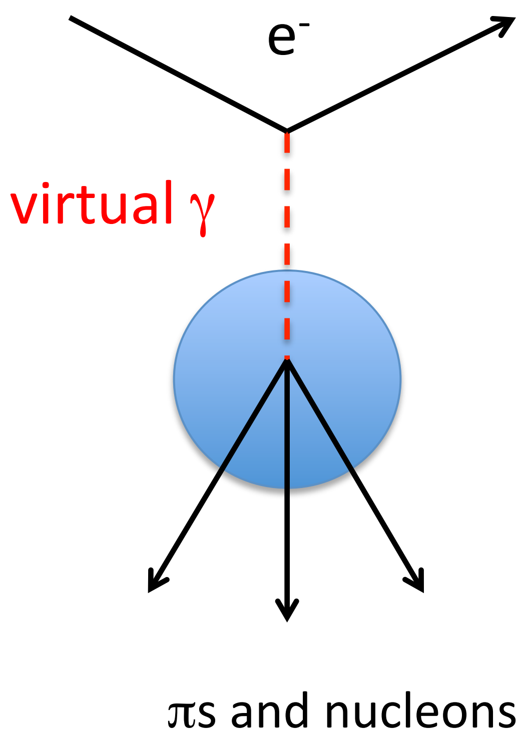
- Electrons and muons cannot interact hadronically, except through virtual photons
  - electron or muon passes by a nucleus and exchanges virtual photon
  - virtual photon then interacts directly with nucleus (or nucleons within nucleus)

Gamma- and Lepto-nuclear Models

Gamma-nuclear



Lepto-nuclear



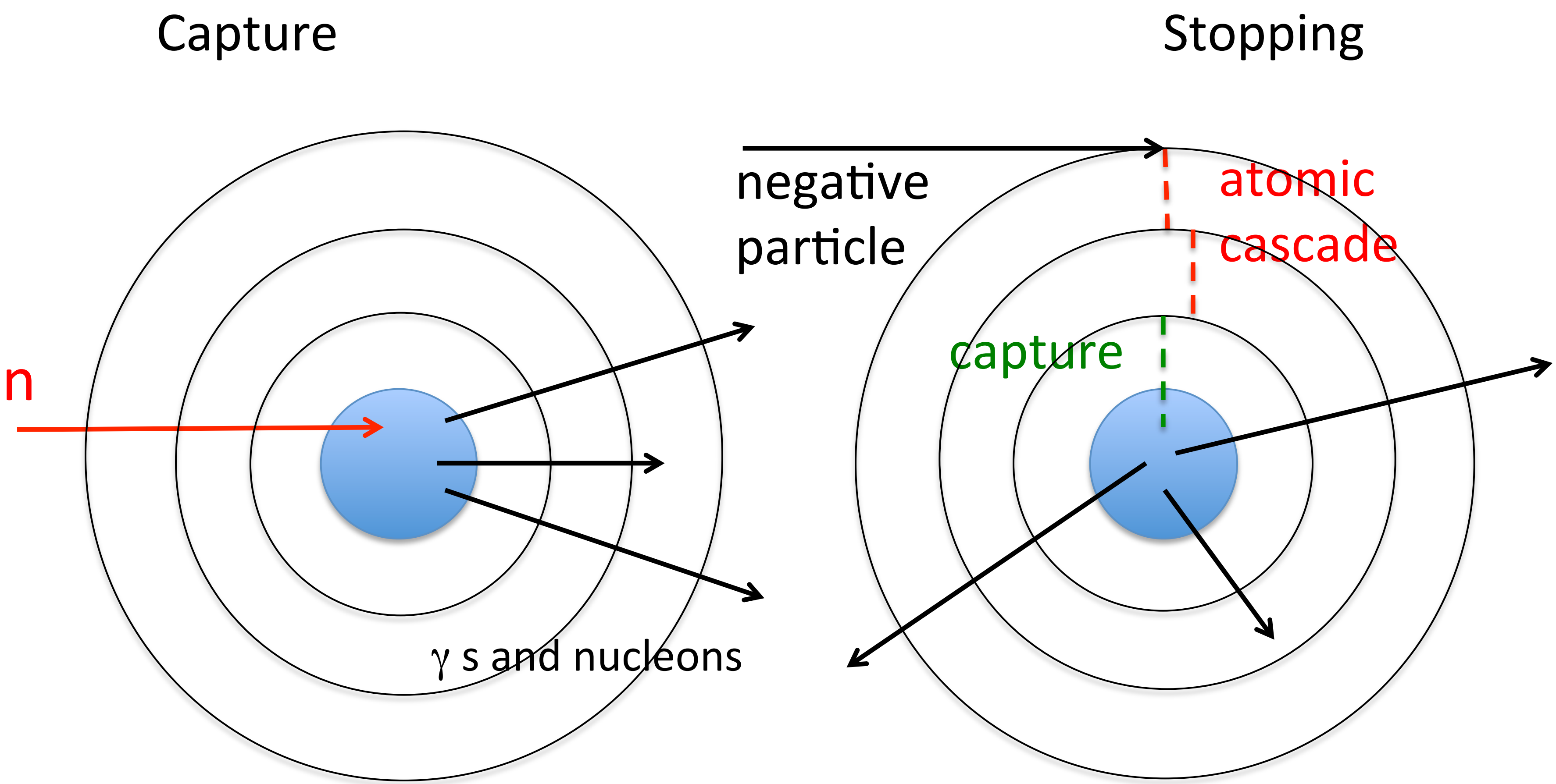
Gamma- and Lepto-nuclear Models

- G4MuonVDNuclearModel
  - Kokoulin model of EM cross section and virtual photon generation
  - Weizsacker-Williams conversion of virtual to real gamma
  - For E_γ < 10 GeV, direct interaction with nucleus using Bertini cascade
  - For E_γ > 10 GeV, conversion of γ to π^0, then interaction with nucleus using FTFP model

- G4ElectroVDNuclearModel
  - Kossov model of EM cross section and virtual photon generation
  - all else identical to that in G4MuonVDNuclearModel

- For gamma-nuclear reaction
  - Bertini cascade below 3.5 GeV
  - QGSP from 3 GeV to 100 TeV

Capture and Stopping Models



Stopped Hadron Models

- G4PiMinusAbsorptionBertini, G4KaonMinusAbsorptionBertini, G4SigmaMinusAbsorptionBertini
  - at rest process implemented with Bertini cascade model
  - G4Precompound model used for de-excitation of nucleus
  - includes atomic cascade but not decay in orbit

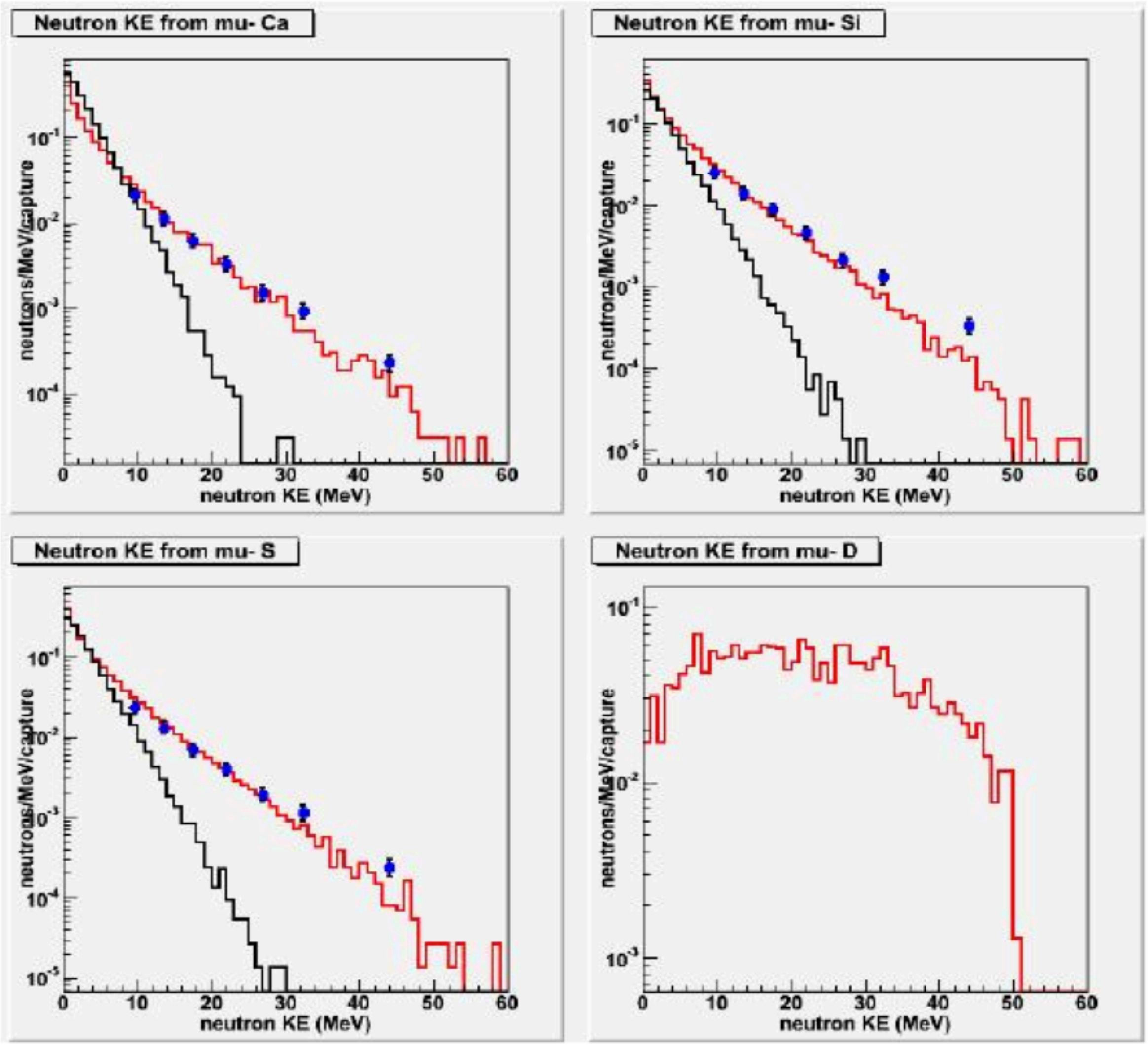
- G4AntiProtonAbsorptionFritiof, G4AntiSigmaPlusAbsorptionFritiof
  - FTF model used because > 2 GeV available in reaction
  - G4Precompound model used for de-excitation of nucleus
  - includes atomic cascade but not decay in orbit

Stopped Muon Models

- G4MuonMinusCapture
  - atomic cascade, with decay in orbit enabled
  - K-shell capture and nuclear de-excitation implemented with Bertini cascade model
  - used in most physics lists

- G4MuonMinusCaptureAtRest
  - atomic cascade, with decay in orbit enabled
  - K-shell capture uses simple particle-hole model
  - nuclear de-excitation handled by G4ExcitationHandler

Muon Capture using Bertini Model (red), old model (black)



Capture Models

- Neutrons, anti-neutrons never really stop, they just slow down from elastic scattering or are absorbed
  - kinetic energy must be taken into account
- G4HadronCaptureProcess
  - in-flight capture for neutrons
  - model implementations:
    - G4ParticleHPCapture (below 20 MeV)
    - G4NeutronRadCapture (all energies)
- G4AntiNeutronAnnihilationAtRest
  - implemented by GHEISHA parameterized model

Fission Processes and Models

- Many hadronic models already include fission implicitly
  - included in nuclear de-excitation code
  - in that case don't add fission process to physics list -> double counting
  - usually only needed in special cases

- G4HadronFissionProcess can use two models
  - G4ParticleHPFission
    - specifically for neutrons below 20 MeV
    - fission fragments produced if desired
  - G4FissLib: Livermore Spontaneous Fission
    - handles spontaneous fission as an inelastic process
    - no fission fragments produced, just neutron spectra

Fission Processes and Models

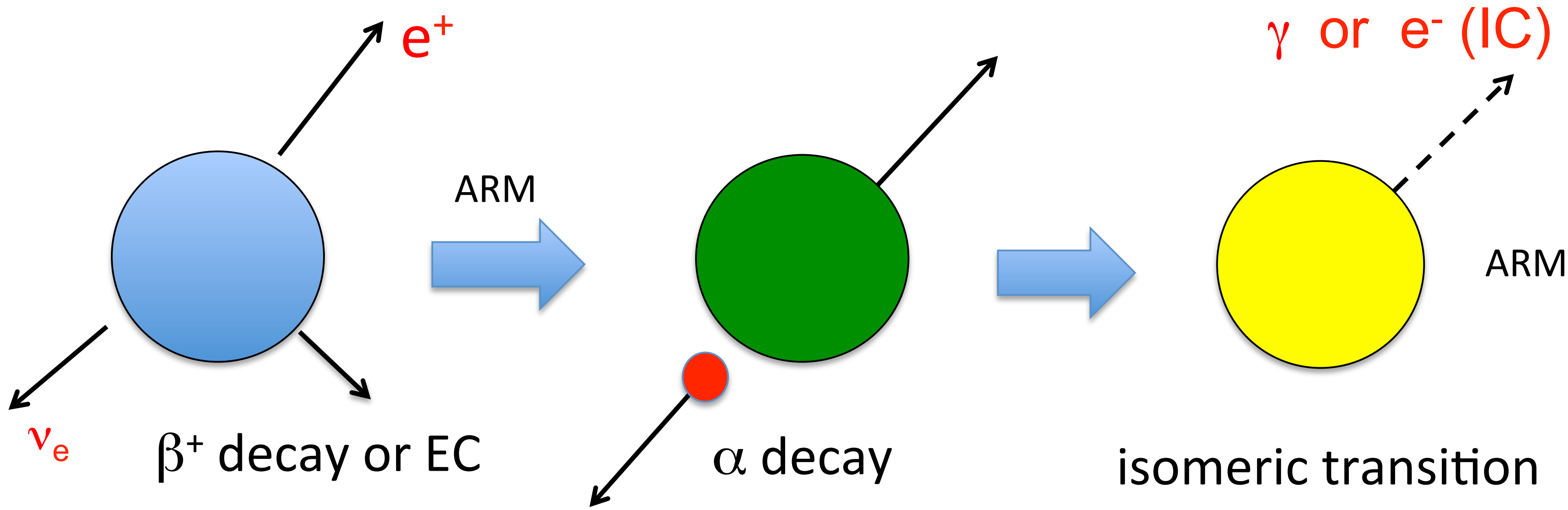
- Fission fragments can be produced with Wendt fission model
  - automatically available when ParticleHPFission is used
  - invoke by setting two environment variables:
    - G4NEUTRONHP_PRODUCE_FISSION_FRAGMENTS
    - G4NEUTRON_HP_USE_WENDT_FISSION_MODEL
  - see extended example geant4/examples/extended/hadronic/FissionFragment

- Model developed by Geant4 user who needed fission fragments in addition to emitted neutrons for reactor studies
  - worked with Geant4 developer and contributed code

Radioactive Decay

- Process to simulate radioactive decay of nuclei
  - in flight
  - at rest
- α, β^+, β^-, γ decay, electron capture (EC) implemented
- Empirical and data-driven
  - data files taken from Evaluated Nuclear Structure Data Files (ENSDF)
    - as of Geant4 10.2, these are in RadioactiveDecay4.3
  - half lives, nuclear level structure for parent and daughter nuclides, decay branching ratios, energy of decay process
  - currently 2792 nuclides, including all meta-stable states with lifetimes > 1 ns

Radioactive Decay Chain



EC: electron capture

IC: internal conversion

ARM: atomic relaxation model

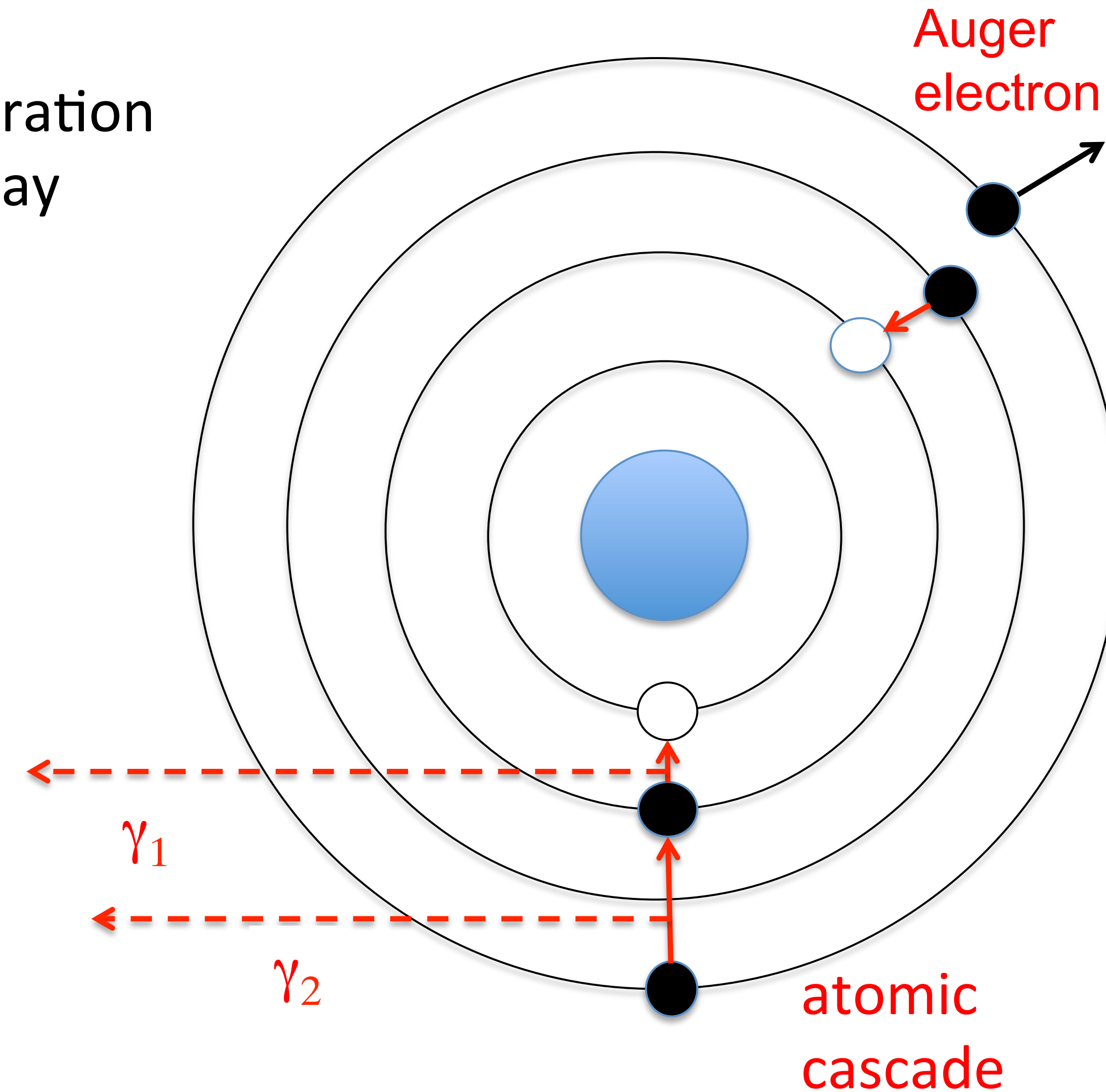
Atomic Relaxation Model

electron shell configuration may change after decay

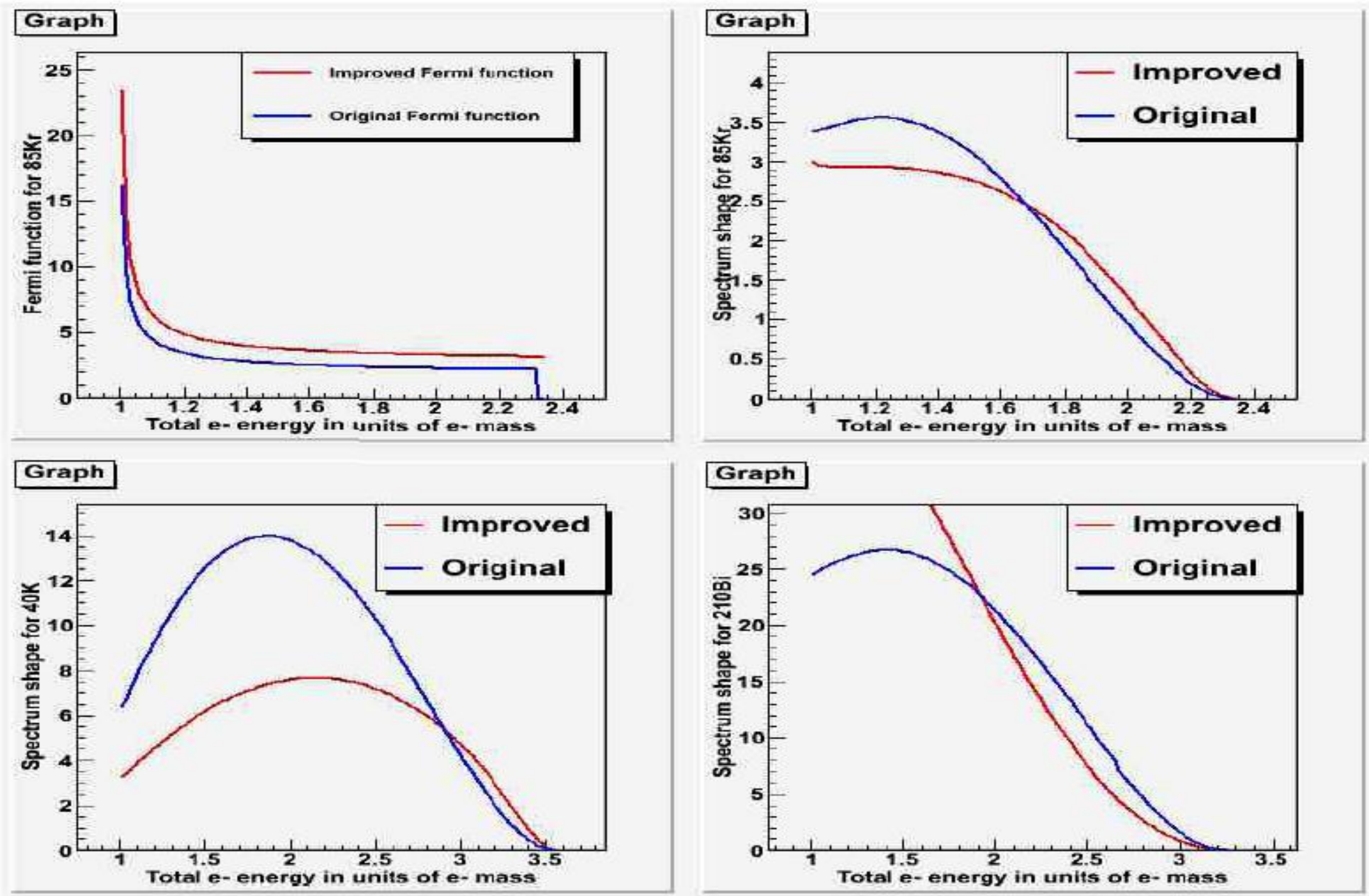
inner holes filled by atomic cascade

either photons or Auger electrons are emitted

fluorescence option also available



β Decay Spectrum Shapes



Gamma (or electron) Emission

- If daughter of nuclear decay is an isomer, prompt de-excitation is done by using G4PhotonEvaporation
  - uses ENSDF files with all known gamma levels for 2071 nuclides
    - as of Geant4 10.0, these are in PhotonEvaporation3.2
  - internal conversion is enabled as a competing process to gamma de-excitation
- Nuclides with LT < 1 ns decay immediately
- Option to enable atomic relaxation after decay
  - atomic cascade
  - Auger
  - fluorescence

Biased Mode

- G4RadioactiveDecay has several biasing options
  - amplify rare decay branches
  - set all decay branches equal
  - "splitting" : perform nuclear decay N times for each event
  - activation: integrate decay chain over time windows using Bateman equations
  - collimation of decay products
  - enable/disable decay in various geometry volumes

- Options activated by UI commands

Using Radioactive Decay

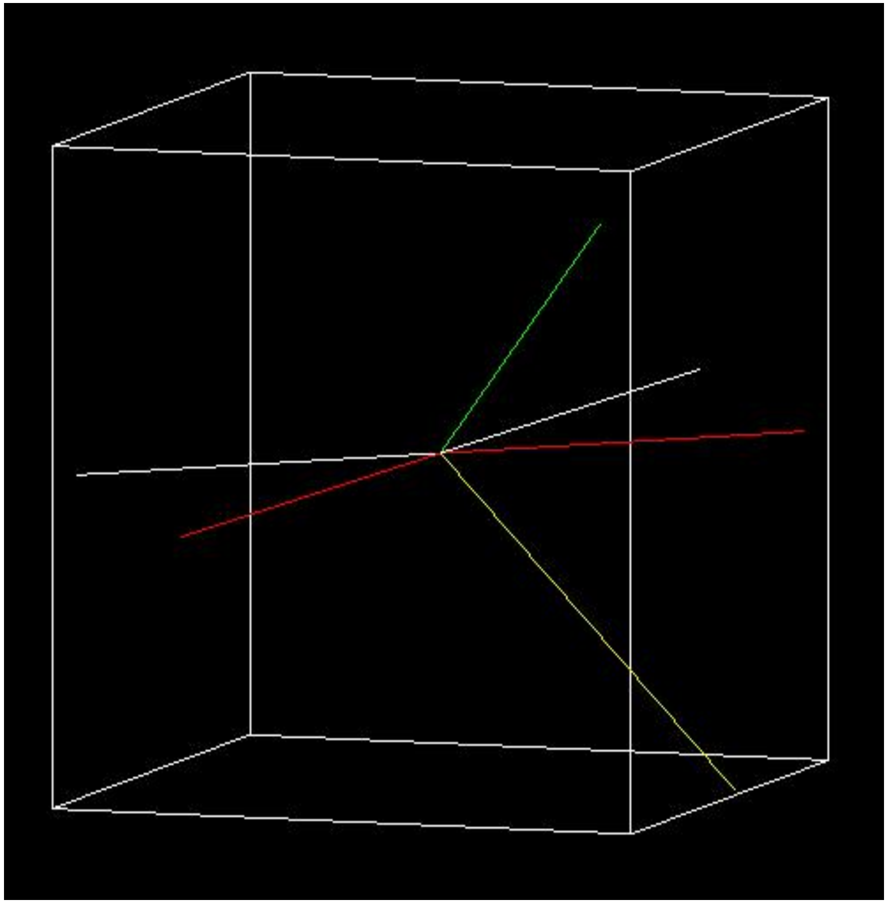
- Can be accessed with messengers (biasing options, etc.)
- To put in your physics list:

```
G4RadioactiveDecay* rDecay = new G4RadioactiveDecay;
G4PhysicsListHelper* plh = G4PhysicsListHelper::GetPhysicsListHelper();
rDecay->SetICM(true);                    // internal conversion
rDecay->SetARM(true);                    // atomic relaxation
plh->RegisterProcess(rDecay, G4GenericIon::G4GenericIon() );
```

- Set environment variables to point to:
  - RadioactiveDecay4.3
  - PhotonEvaporation3.2

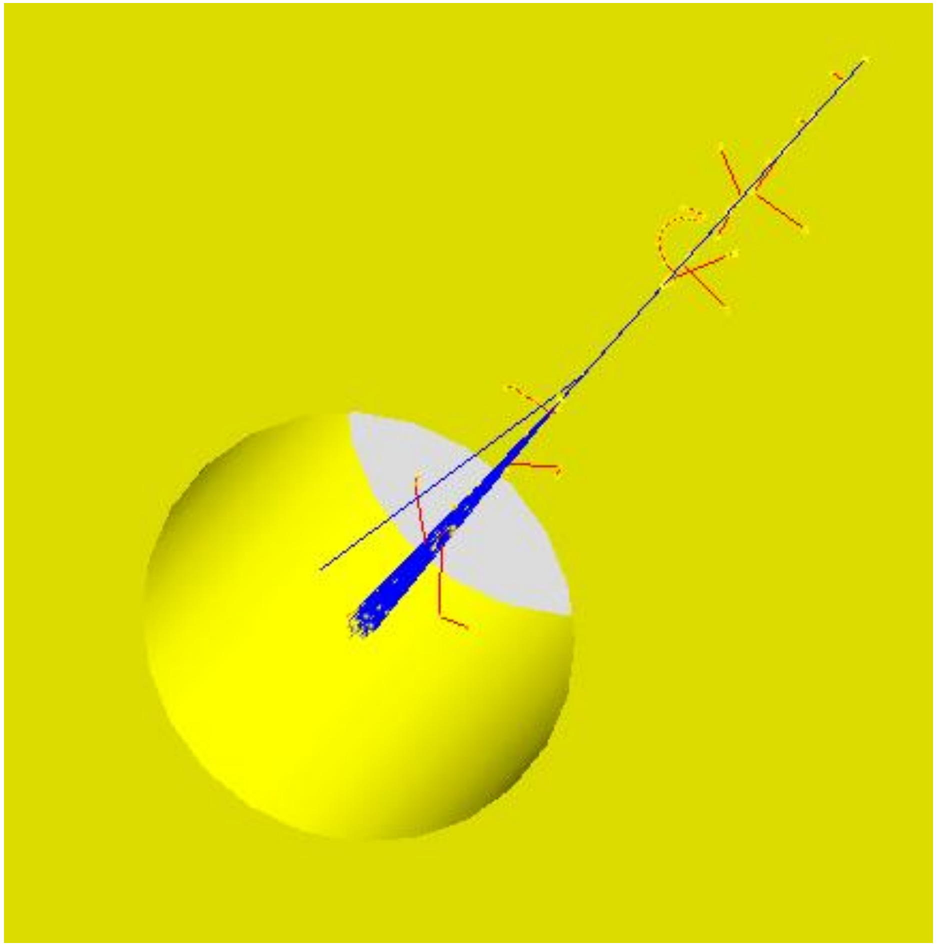
Examples Using RDM

- /examples/extended/radioactivedecay/rdecay01
  - 2 x 2 x 2 mm box of air
  - only radioactive decay and transportation enabled
  - default: decay of ^{210}Pb at origin of box
  - user-defined decay files
  - analysis options: energy, lifetime histograms
  - visualization



Examples Using RDM

- /examples/extended/radioactivedecay/rdecay02
  - CsI cylindrical target at center of detector tube made of Ge
  - physics
    - induced radioactivity
    - radioactive decay + standard EM
    - option to use full physics list
  - Generalized Particle Source fires 1 GeV p
  - analysis options: energy histograms, pulse height spectra



Summary

- Two QCD string models available for high energy interactions
- Gamma-nuclear and lepto-nuclear processes are available
  - for γ, e^-, e^+, μ^-, μ^+ projectiles
- Several stopping processes and models available
  - for μ^-, π^-, K^-, Σ^-, anti-p, anti-Σ^+
- Capture process and models exist for n, anti-n
- Fission
  - be sure not to double-count
  - model now available to produce fission fragments
- The radioactive decay process is quite detailed and has many recent improvements