Geant4 11.2.p01

Hadronic Physics III

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Geant4 Tutorial at Jefferson Lab

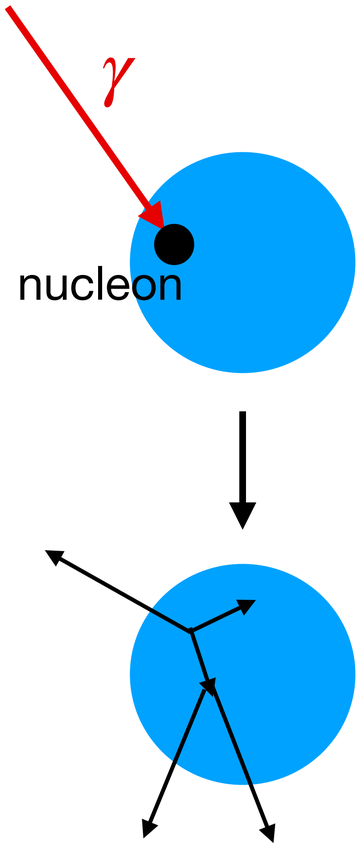
28 March 2024

Outline

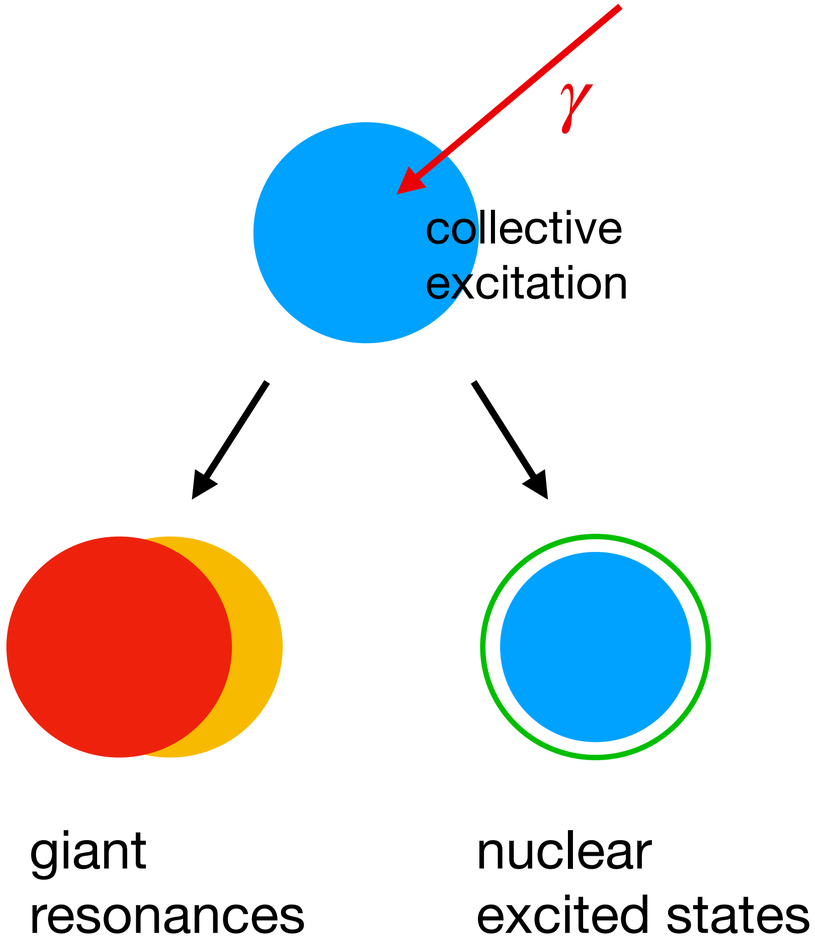
- Gamma-nuclear models
- Lepto-nuclear models
- Radioactive Decay

Gamma-nuclear

High Energy



Low Energy



Gamma-nuclear Process and Models

- 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
- Reactions handled by G4HadronInelasticProcess
  - if no hadron emission, handled by EM process
- Process implemented by cross section sets
  - G4PhotoNuclearCrossSection - CHIPS parameterization of photonuclear cross sections, all energies
  - G4GammaNuclearXS:
    - IAEA photonuclear database for E < 150 MeV
    - G4PhotoNuclearCrossSection for E > 150 MeV
- and three models
  - G4LowEGammaNuclearModel (< 200 MeV)
    - uses gamma energy to set nuclear excitation, then decays by G4Precompound model
  - Bertini cascade (200 MeV < E < 3.5 GeV)
    - interacts gamma directly with nucleon using parameterized cross sections
  - Quark-Gluon-String (GQS) (E > 3.5 GeV)
    - treats gamma as a hadron

LEND Gamma-nuclear

- As for low energy neutrons, there are high precision LEND-GIDI cross sections and models for photons
  - can be used now, but new, improved models on their way (June 2024)
  - mostly below 20 MeV

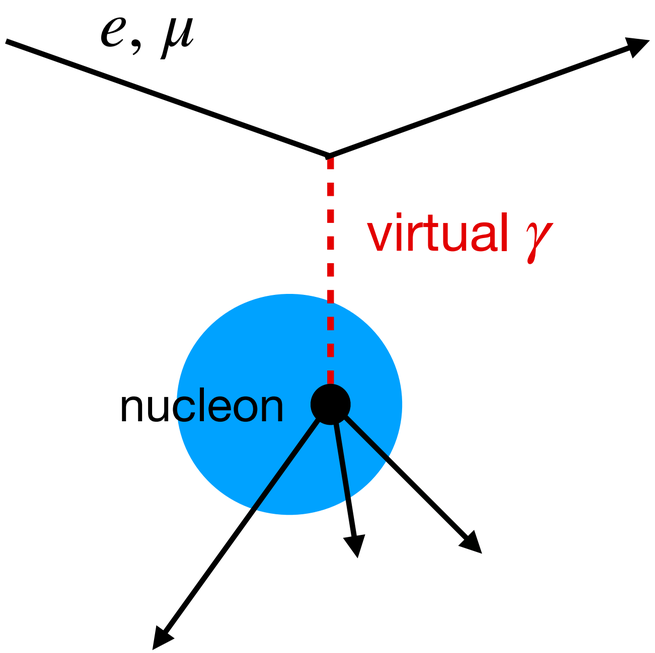
- Reactions handled by G4HadronInelasticProcess

- Process implemented by
  - cross sections from GNDS database
  - G4LENDGammaModel (derived from G4LENDModel)

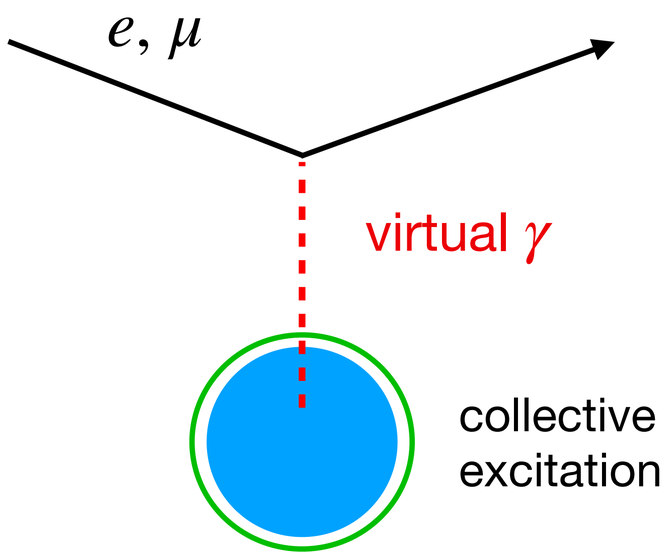
- Also by G4LENDorBERTModel
  - GNDS database does not yet cover all nuclei, so LEND cannot always be used
  - in that case, invoke Bertini

Lepto-nuclear

High Energy Transfer



Low Energy Transfer



Lepto-nuclear Process and Models

- Electrons and muons cannot interact hadronically, except through virtual photons
  - lepton passes by nucleus, exchanging virtual photon
  - virtual photon interacts with nucleus (low energy) or nucleon (high energy)

- Reactions handled by G4HadronInelasticProcess
  - implemented by muon model or electron model

- G4MuonVDNuclearModel
  - Kokoulin model of EM cross section and virtual photon generation
  - Weizsacker-Williams conversion of virtual gamma to real gamma
  - for $E_\gamma < 10$ GeV, direct interaction with nucleus using Bertini cascade
  - for $E_\gamma > 10$ GeV, conversion γ to π followed by interaction with nucleus using FTF model

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

Full Electro-nuclear Scattering

- G4ElectroVDNuclearModel makes crude approximations

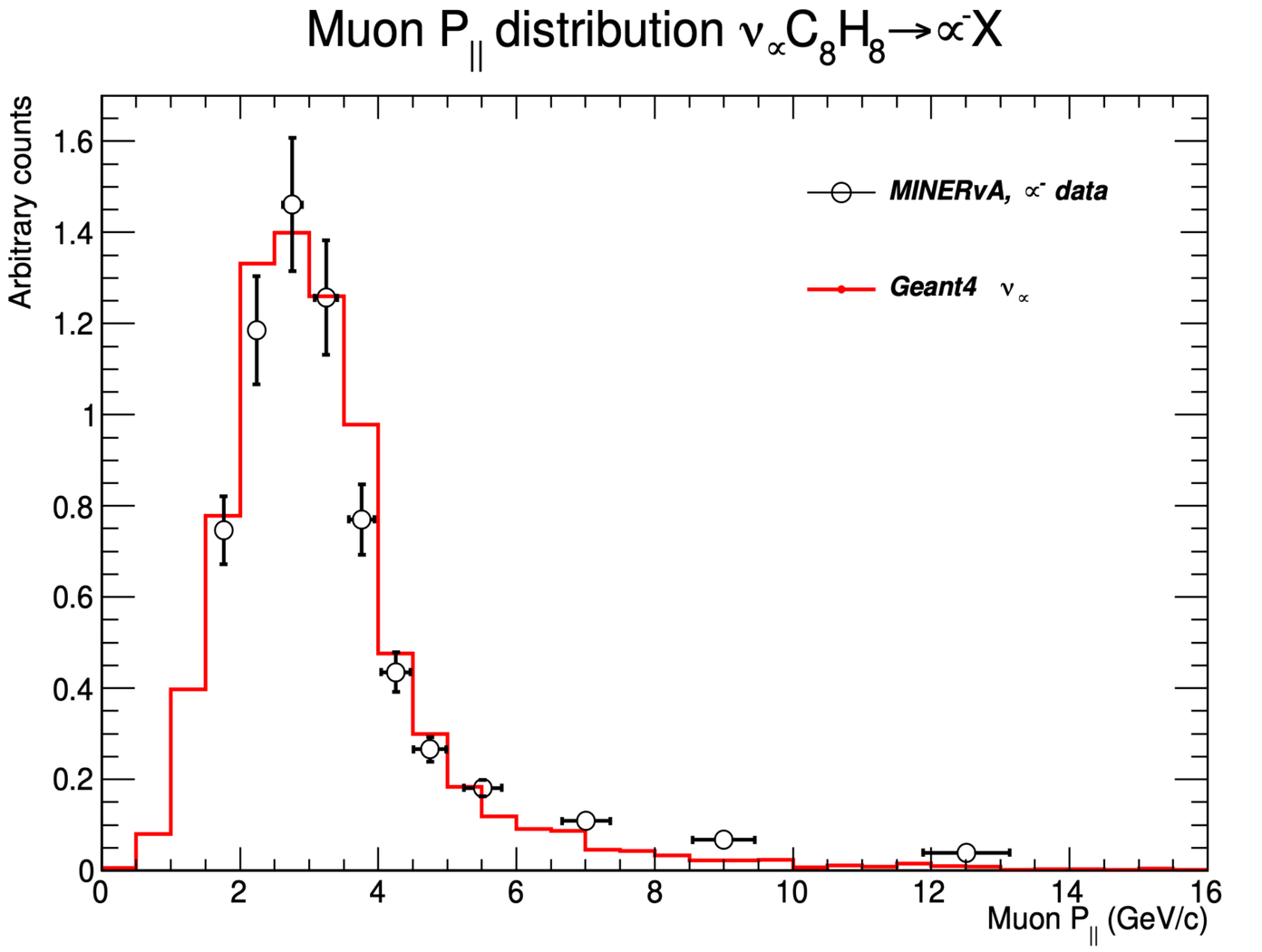
- Full model of electron scattering from nuclei is needed
  - direct interaction of off-shell virtual photon with nucleus/nucleons (no real photon approximations)
  - nuclear and nucleon structure functions

- No models for this yet in Geant4
  - under development
  - needs manpower

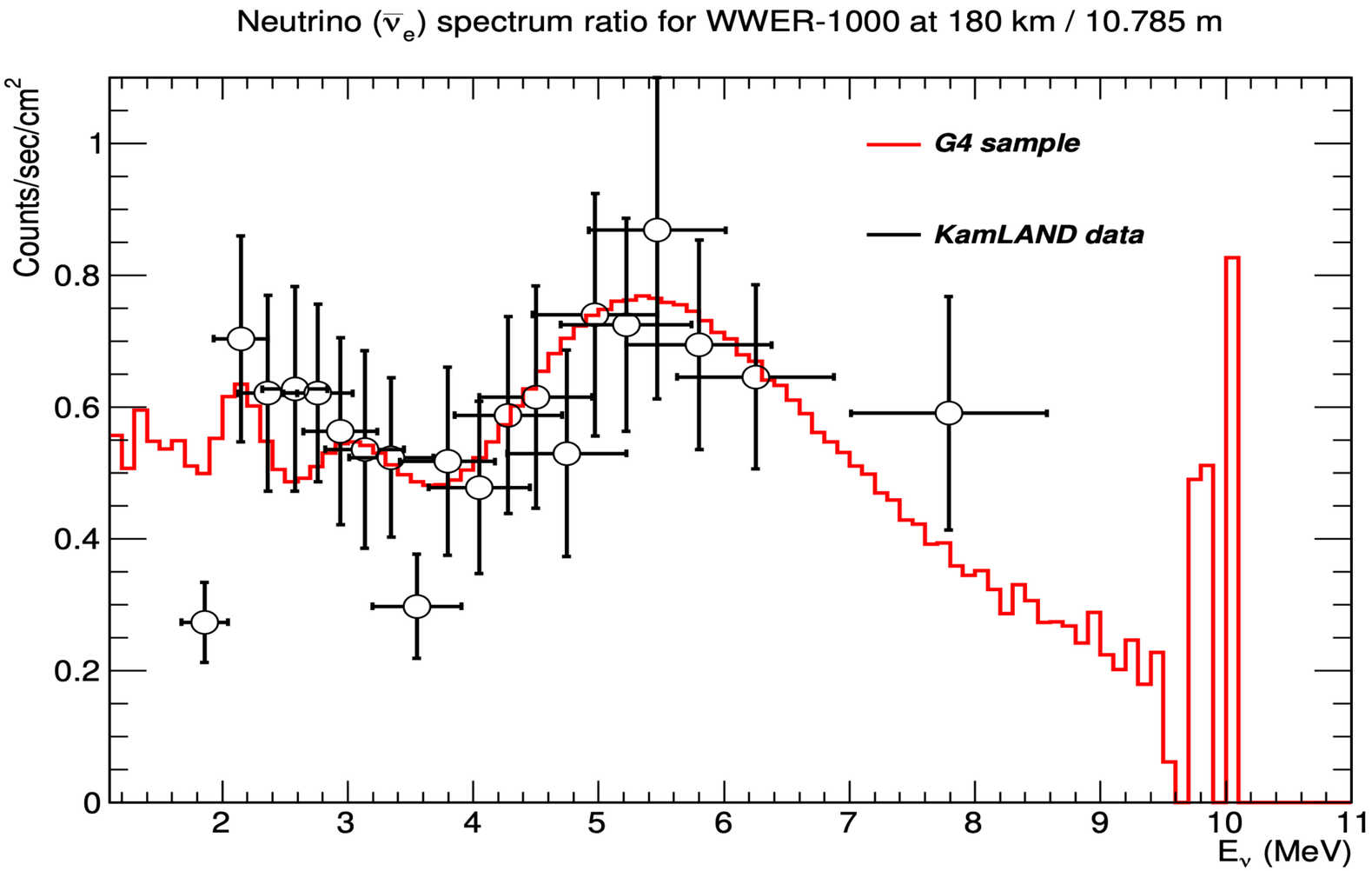
Neutrino Scattering

- Models available for ν_e , $\overline{\nu_e}$, ν_μ , $\overline{\nu_\mu}$, ν_τ , $\overline{\nu_\tau}$ scattering from nuclei
  - charged and neutral current varieties - 12 models in all
- Virtual photons $(\omega, \mathbf{q})$ sampled for ν - nucleus interaction
  - implemented by muon model or electron model
- Charged current models
  - e, μ, τ emitted plus 1 pion (coherent or resonant)
  - G4Precompound model used to de-excite residual nucleus
  - final state interactions within nucleus not included for DIS
- Neutral current models
  - same as CC models, but with ν_e , $\overline{\nu_e}$, ν_μ , $\overline{\nu_\mu}$, ν_τ , $\overline{\nu_\tau}$ emitted
- Biased cross sections
  - ν cross sections very small
  - -> Geant4 tracking requires biasing in G4Region of detector (typically 5×10^{14} for neutral current)
  - done in physics list through UI commands

ν_μ Quasi-elastic Scattering



Can do oscillations, too ($\overline{\nu_\mu} \rightarrow \overline{\nu_e}$)



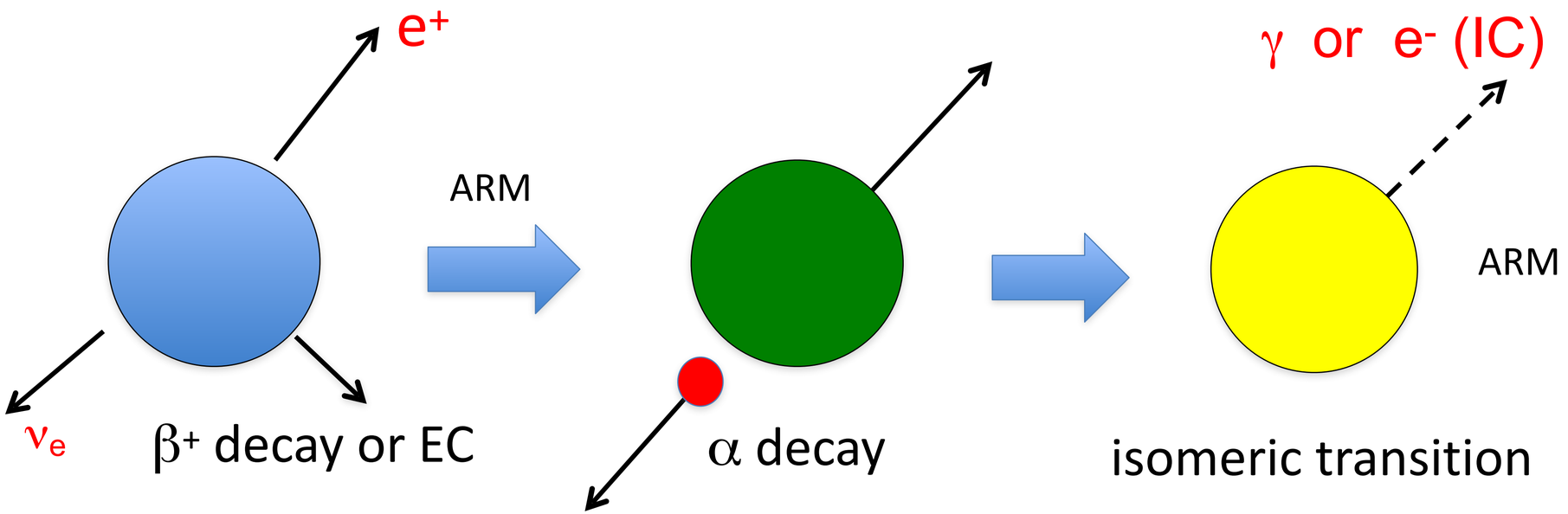
Radioactive Decay

- Process to simulate radioactive decay of nuclei
  - in flight
  - at rest

- α, β^+, β^-, γ decay (IT), electron capture (EC) and spontaneous fission implemented

- Empirical and data-driven
  - data files taken from Evaluated Nuclear Structure Data Files (ENSDF)
    - as of Geant4 11.2, these are in RadioactiveDecay5.6
  - half lives, nuclear level structure for parent and daughter nuclides, decay branching ratios, energy of decay process
  - currently 2990 nuclides, including all meta-stable states with lifetimes > 1 ns

Radioactive Decay Chain Example

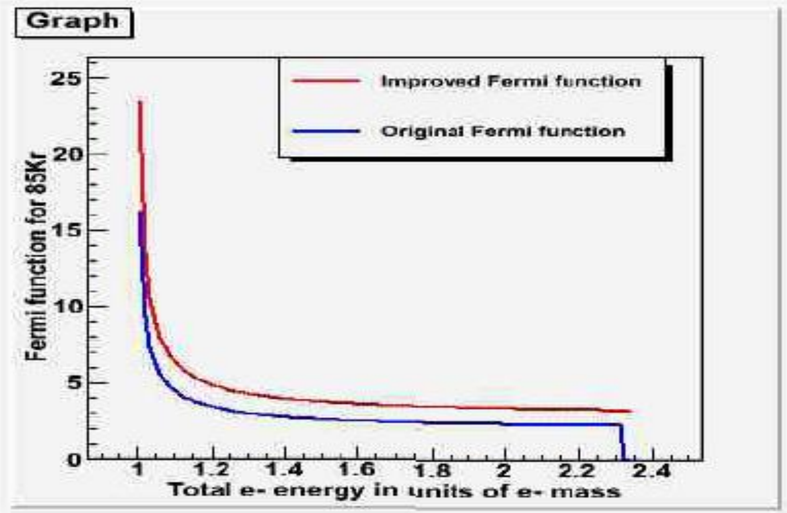


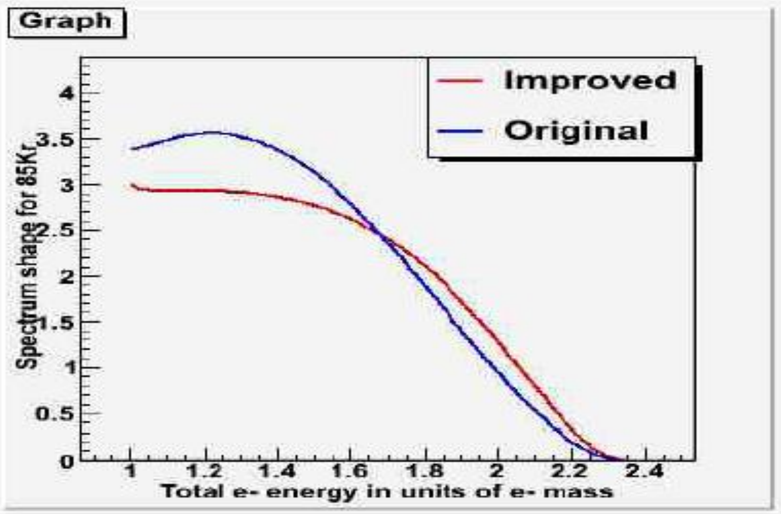
EC: electron capture

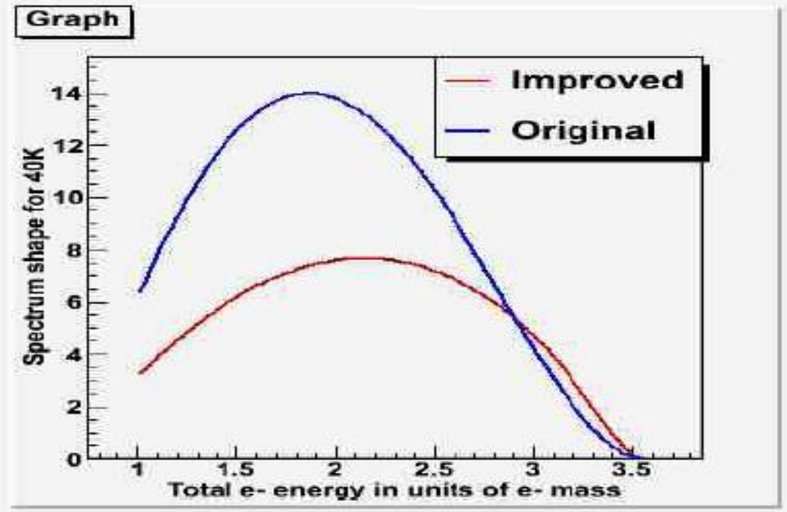
IC: internal conversion

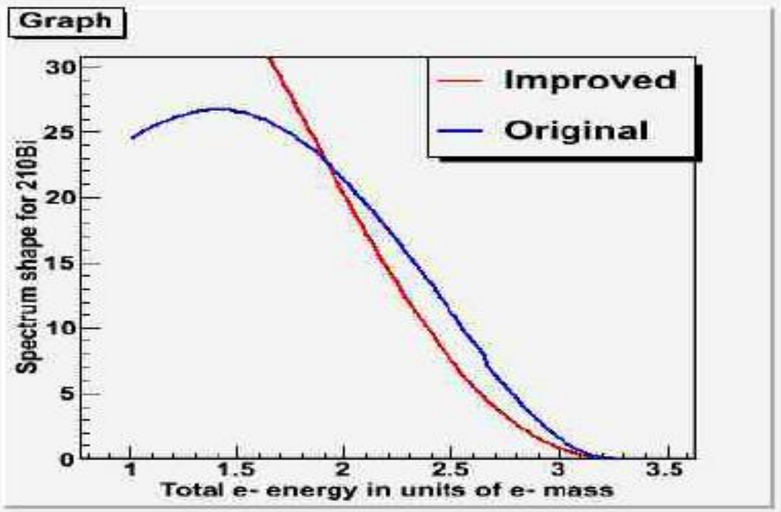
ARM: atomic relaxation model

β Decay Spectrum Shapes









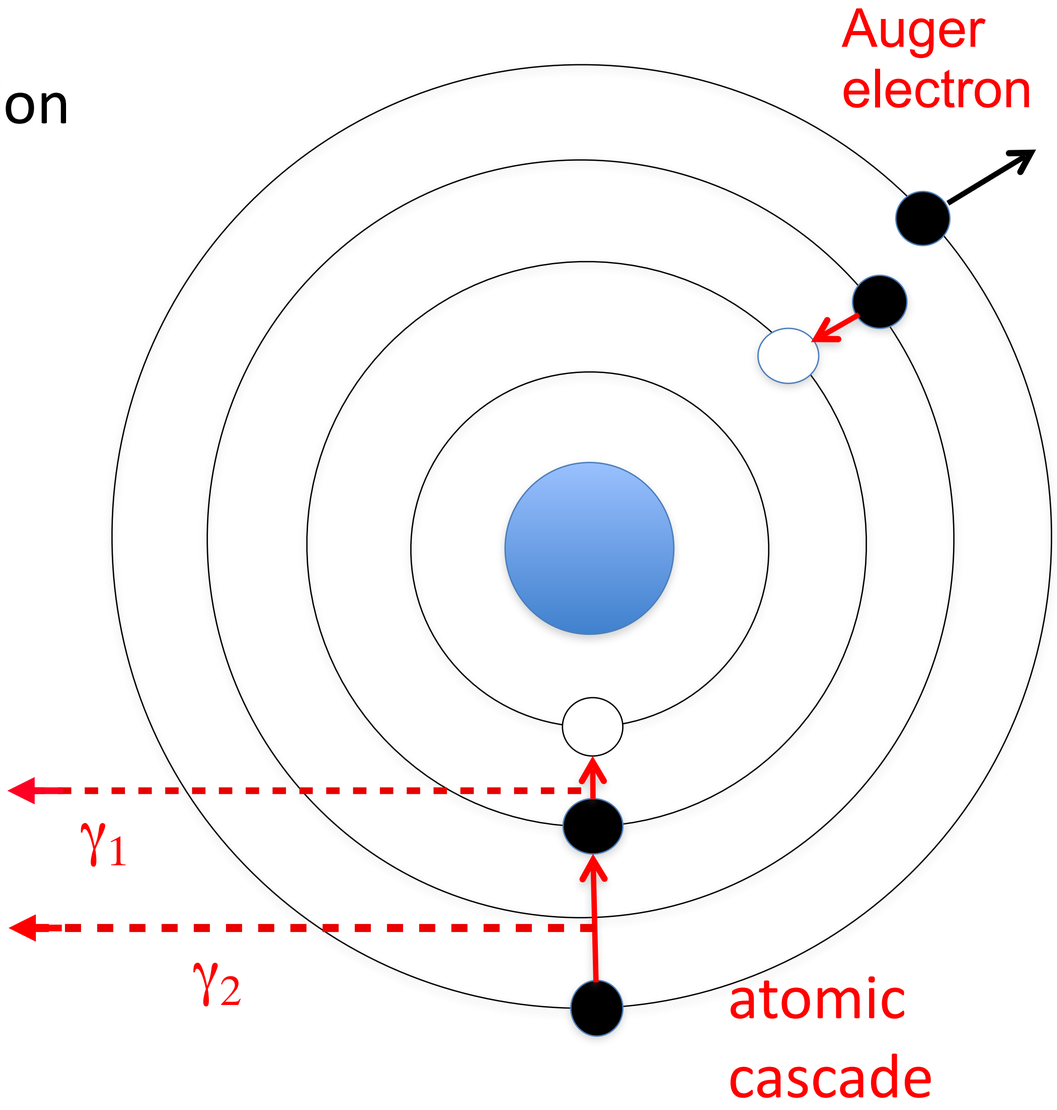
Atomic Relaxation Model

electron shell configuration may change after decay

inner holes filled by atomic cascade

either photons or Auger electrons are emitted

fluorescence option also available



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 3172 nuclides
    - as of Geant4 11.2, these are in PhotonEvaporation5.7
  - 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 emission
  - 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 or directly in physics list
- G4Radioactivation
  - does all decay chains specified by user in one step
  - useful for activation and dose studies

Using Radioactive Decay Process

- 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:
  - RadioactiveDecay5.6
  - PhotonEvaporation5.7

Summary

- Gamma-nuclear process
  - low, medium, high energy models
  - GIDI-LEND models for high-precision photo-nuclear undergoing major update, available June 2024
- Lepto-nuclear process
  - Muon-nuclear and electro-nuclear with conversion of virtual photon to real
  - Electro-nuclear with full 4-momentum transfer and nuclear structure not yet available
  - Neutrino-nuclear models available
    - charged current
    - neutral current
    - oscillations
    - cross section biasing
- Radioactive decay
  - α, β, IT, EC and spontaneous fission decays available with or without atomic relaxation
  - can run in biased or analog mode