Hadronic Physics III

Geant4 Tutorial at MIT

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Dennis Wright
Outline

• QCD string models

• Gamma- and lepto-nuclear models

• Capture, Stopping and Fission models

• Radioactive decay
High Energy Nuclear Interaction

![Diagram](image)

- **Excited String**
- **Nucleon**
- **Projectile**

Diagram illustrating the interaction process in high energy nuclear reactions.
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
  • $n + n \rightarrow n\Delta$, NN, ΔΔ, NΔ, …
  • essentially a quark-level cascade in vicinity of path $\rightarrow$ 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
  • $p, n, \pi, K, \Lambda, \Sigma, \Omega$ from 3 GeV to $\sim$TeV
  • anti-proton, anti-neutron, anti-hyperons at all energies
  • anti-$d$, anti-$t$, anti-$^3\text{He}$, anti-$\alpha$ with momenta between 150 MeV/nucleon and 2 GeV/nucleon

• Quark-Gluon String (QGS) valid for
  • $p, n, \pi, K$ from 15 GeV to $\sim$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
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

\[ \gamma \rightarrow \pi s \text{ and nucleons} \]

\[ e^{-} \rightarrow \text{virtual } \gamma \]

\[ \pi s \text{ and nucleons} \]
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 $E_\gamma < 10$ GeV, direct interaction with nucleus using Bertini cascade
  - For $E_\gamma > 10$ GeV, conversion of $\gamma$ to $\pi^0$, 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

Capture

Capture

Stopping

n

γ s and nucleons

negative particle

atomic cascade

capture

Capture and Stopping Models

Capture

Capture

Stopping

n

γ s and nucleons

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capture
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
- $\alpha$, $\beta^+$, $\beta^-$, $\gamma$ 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/radioactive_decay/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 $\gamma$, $e^-$, $e^+$, $\mu^-$, $\mu^+$ projectiles
• Several stopping processes and models available
  • for $\mu^-$, $\pi^-$, $K^-$, $\Sigma^-$, anti-p, anti-$\Sigma^+$
• 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