Outline

• Overview of hadronic physics
  • processes, cross sections, models
  • hadronic framework and organization

• Precompound models
  • and de-excitation models

• Cascade models
  • Bertini-style, binary, INCL++
Hadronic Processes, Models and Cross Sections

- In Geant4 physics is assigned to a particle through processes.
- Each process may be implemented:
  - directly, as part of the process, or
  - in terms of a model class.
- Geant4 often provides several models for a given process:
  - user must choose
  - can, and sometimes must, have more than one per process.
- A process must also have cross sections assigned:
  - here too, there are options.
Cross Sections

• Default cross section sets are provided for each type of hadronic process
  • fission, capture, elastic, inelastic
  • can be overridden or completely replaced

• Different types of cross section sets
  • some contain only a few numbers to parameterize the c.s.
  • some represent large databases
  • some are purely theoretical (equation-driven)
Alternative Cross Sections

• Low energy neutrons
  • G4NDL available as Geant4 distribution files
  • Livermore database (LEND) also available
  • available with or without thermal cross sections

• Medium energy neutron and proton reaction cross sections
  • $14 \text{ MeV} < E < 20 \text{ GeV}$

• Ion-nucleus reaction cross sections
  • Tripathi, Shen, Kox
  • good for $E/A < 10 \text{ GeV}$

• Pion reaction cross sections
Cross Section Management

GetCrossSection() sees last set loaded within energy range

Load sequence

Set 1

Set 2

Set 3

Set 4

Default cross section set

Energy
Data-driven Hadronic Models

• Characterized by lots of data
  • cross sections
  • angular distributions
  • multiplicities, etc.

• To get interaction length and final state, models depend on interpolation of data
  • cross sections, Legendre coefficients

• Examples
  • neutrons (E < 20 MeV)
  • coherent elastic scattering (pp, np, nn)
  • radioactive decay
Theory-driven Hadronic Models

• Dominated by theoretical arguments (QCD, Glauber theory, exciton theory...)

• Final states (number and type of particles and their energy and angular distributions) determined by sampling theoretically calculated distributions

• This type of model is preferred, as it is the most predictive

• Examples
  • quark-gluon string (projectiles with $E > 20$ GeV)
  • intra-nuclear cascade (intermediate energies)
  • nuclear de-excitation and break-up
Partial Hadronic Model Inventory

- At rest absorption, $\mu$, $\pi$, $K$, anti-p
- Radioactive decay
  - High Prec. Particle
  - LEND
  - High prec. neutron
    - Evaporation
    - Fermi breakup
    - Multifragment
    - Photon Evap
    - Pre-compound
  - INCL++
    - Binary cascade
    - Bertini-style cascade
  - Photo-nuclear, electro-nuclear, muon-nuclear
  - Electro-nuclear dissociation
  - QMD (ion-ion)
  - Wilson Abrasion
  - Quark Gluon string
  - Fritiof string

Energy scales:
- 1 MeV
- 10 MeV
- 100 MeV
- 1 GeV
- 10 GeV
- 100 GeV
- 1 TeV
Model Management

Model returned by GetHadronicInteraction()

Model 1
Model 3
Model 4
Model 2

Energy
Hadronic Interactions from TeV to meV

TeV hadron

dE/dx $\sim A^{1/3}$ GeV

~100 MeV to ~10 MeV

p, n, d, t, $\alpha$

~10 MeV to thermal

~GeV to ~100 MeV

$\gamma$ and n
Precompound Models

• G4PrecompoundModel is used for nucleon-nucleus interactions at low energy and as a nuclear de-excitation model within higher-energy codes
  • valid for incident p, n from 0 to 170 MeV
  • takes a nucleus from a highly excited set of particle-hole states down to equilibrium energy by emitting p, n, d, t, $^3$He and $\alpha$
  • once equilibrium is reached, four sub-models are called to take care of nuclear evaporation and break-up
    • these 4 models not currently callable by users

• Two Geant4 cascade models have their own version of nuclear de-excitation models embedded in them
De-excitation Models

- Four sub-models typically used to de-excite a remnant nucleus
  - Fermi break-up
  - photon evaporation
  - multi-fragmentation
  - fission

- These models are not intended to be assigned directly to a process
  - instead they are meant to be linked together and then assigned to the G4Precompound model through the class G4ExcitationHandler
De-excitation Model Details

- **Fermi break-up**
  - remnant nucleus is destroyed – nothing left but p, n, t, a
  - valid only for $A < 17$ and high excitation energies

- **Fission**
  - splits excited nucleus and emits fission fragments $+ n$
  - valid only for $A > 65$

- **Multi-fragmentation**
  - statistical breakup model with propagation of fragments in Coulomb field
  - for excitation energies $E/A > 3$ MeV
De-excitation Model Details

• Photon evaporation
  • usually final stage of nuclear de-excitation
  • data-driven: uses ENSDF database
    • currently have up to hundreds of gamma levels for 2071 nuclides in PhotonEvaporation3.1
  • handles gamma cascades, does electron emission in case of internal conversion
  • currently no correlation when more than one gamma emitted (but that’s coming)
Precompound Models

• Invocation of Precompound model:
  G4ExcitationHandler* handler = new G4ExcitationHandler;
  G4PrecompoundModel* preco = new G4PrecompoundModel(handler);
  // Create de-excitation models and assign them to precompound model

  G4NeutronInelasticProcess* nproc = new G4NeutronInelasticProcess;
  nproc->RegisterMe(preco);
  neutronManager->AddDiscreteProcess(nproc);
  // Register model to process, process to particle

• Here the model is invoked in isolation, but usually it is used in combination with high energy or cascade models
  • a standard interface exists for this
Intra-nuclear Cascade Models

• Typical intra-nuclear cascade energies are inconvenient
  • too high for nuclear physics treatments
  • too low for QCD

• Must use Monte Carlo techniques to propagate hadrons within the target nucleus in order to produce a final state
  • “Monte Carlo within a Monte Carlo”
  • one of the first applications of Monte Carlo methods to nuclear interactions
  • time-consuming

• Specific channels not produced
  • do not use data to produce, for example $^{14}\text{N}(p,n)^{14}\text{O}$
Bertini-style Cascade Model

• A classical (non-quantum mechanical) cascade
  • average solution of a particle traveling through a medium (Boltzmann equation)
  • no scattering matrix calculated
  • can be traced back to some of the earliest codes (1960s)

• Core code:
  • elementary particle collisions with individual protons and neutrons: free space cross sections used to generate secondaries
  • cascade in nuclear medium
  • pre-equilibrium and equilibrium decay of residual nucleus
  • target nucleus built of three concentric shells
Bertini Cascade (0 < E < 10 GeV)

1 to 3 uniform density shells

p, n, d, t, α

γ and n
Using the Bertini Cascade

- In Geant4 the Bertini cascade is used for p, n, π⁺, π⁻, K⁺, K⁻, K⁰_L, K⁰_S, Λ, Σ⁰, Σ⁺, Σ⁻, Ξ⁰, Ξ⁻, Ω⁻
  - valid for incident energies of 0 – 10 GeV
  - can also be used for gammas

- Invocation sequence

  G4CascadeInterface* bert = new G4CascadeInterface;
  G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess;
  pproc->RegisterMe(bert);
  protonManager->AddDiscreteProcess(pproc);
  // same sequence for all other hadrons and gamma
Validation of Bertini Cascade
Binary Cascade Model

• Modeling sequence similar to Bertini, except
  • it’s a time-dependent model
  • hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
  • particles follow curved trajectories in smooth nuclear potential

• Binary cascade is currently used for incident p, n and π
  • valid for incident p, n from 0 to 10 GeV
  • valid for incident π⁺, π⁻ from 0 to 1.3 GeV

• A variant of the model, G4BinaryLightIonReacFon, is valid for incident ions up to A = 12 (or higher if target has A < 12)
Using the Binary Cascade

- Invocation sequence:
  ```
  G4BinaryCascade* binary = new G4BinaryCascade();
  G4PionPlusInelasticProcess* piproc =
      new G4PionPlusInelasticProcess();
  piproc->RegisterMe(binary);
  piplus_Manager->AddDiscreteProcess(piproc);
  ```
- Invoking BinaryLightIonReaction
  ```
  G4BinaryLightIonReaction* ionBinary =
      new G4BinaryLightIonReaction();
  ionProc->RegisterMe(ionBinary);
  genericIonManager->AddDiscreteProcess(ionProc);
```
Validation of Binary Cascade
256 MeV protons

\[ \frac{d\sigma}{dE_d\Omega} \text{ [mb/MeV/Sr]} \]

neutron yield at 7.5°

Binary Cascade

- Be
- Al
- Fe
- Pb

\[ E_{\text{kin}} \text{ [MeV]} \]
INCL++ Cascade Model

- Model elements
  - time-dependent model
  - smooth Woods-Saxon or harmonic oscillator potential
  - particles travel in straight lines through potential
  - delta resonance formation and decay (like Binary cascade)

- Valid for incident p, n and π, d, t, \(^3\)He, α from 150 MeV to 10 GeV
  - also works for projectiles up to \(A = 12\)
  - targets must be 11 < \(A < 239\)
  - ablation model (ABLA) can be used to de-excite nucleus

- Used successfully in spallation studies
  - also expected to be good in medical applications
Validation of INCL++ Model
Spallation residues from $p + {}^{208}\text{Pb}$
Summary (1)

• Geant4 hadronic physics allows user to choose how a physics process should be implemented
  • cross sections
  • models
• Many processes, models and cross sections to choose from
  • hadronic framework makes it easier for users to add more
• Precompound models are available for low energy nucleon projectiles and nuclear de-excitation
  • de-excitation sub-models handle the decay after the precompound stage
Summary (2)

- Three intra-nuclear cascade models available to cover medium energies (up to 10 GeV)
  - Bertini-style
  - Binary cascade
  - INCL++