Outline

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

• **Elastic scattering**

• **Precompound models**

• **The cascade models**
  - Bertini, binary, INCL/ABLA

• **Parameterized models**
  - high energy, low energy
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

In Geant4 hadronic physics there are sometimes many models for a given process
- user must choose
- can have more than one per process

A process must also have cross sections assigned
- here too, there are options
particle

at rest
process 1

in-flight
process 2

process
3

process
n

model 1
model 2
·
model n

model 1
c.s. set 1
·
c.s. set n

c.s. set 2
c.s. set 2
·
c.s. set n

Energy range
manager

Cross section
data store
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 c.s.
- some represent large databases
- some are purely theoretical
Alternative Cross Sections

Low energy neutrons

- G4NDL available as Geant4 distribution data files
- Available with or without thermal cross sections

“High energy” neutron and proton reaction $\sigma$

- $14 \text{ MeV} < E < 20 \text{ GeV}$

Ion-nucleus reaction cross sections

- Good for $E/A < 10 \text{ GeV}$

Pion reaction cross sections
Cross Section Management

GetCrossSection() sees last set loaded for energy range

Load sequence

Set 1

Set 2

Set 3

Set 4

Baseline Set

Energy
Hadronic Models – Data Driven

Characterized by lots of data
- cross section
- angular distribution
- multiplicity
- etc.

To get interaction length and final state, models interpolate data
- cross section, coefficients of Legendre polynomials

Examples
- neutrons (E < 20 MeV)
- coherent elastic scattering (pp, np, nn)
- Radioactive decay
Hadronic Models – Theory Driven

Dominated by theory (quark-gluon strings, chiral perturbation theory, ...)
- not as much data to tie things down

Final states determined by sampling theoretical distributions

Examples:
- quark-gluon string (projectiles with $E > 20$ GeV)
- intra-nuclear cascade (intermediate energies)
- nuclear de-excitation and breakup
- chiral invariant phase space (up to a few GeV)
Hadronic Models - Parameterized

• Depend mostly on fits to data and some theoretical distributions

• Two models available:
  - Low Energy Parameterized (LEP) for < 20 GeV
  - High Energy Parameterized (HEP) for > 20 GeV
  - Each type refers to a collection of models

• Both derived from GHEISHA model used in Geant3

• Core code:
  - hadron fragmentation
  - cluster formation and fragmentation
  - nuclear de-excitation
Model Management

Model returned by GetHadronicInteraction()

Model 1

Model 3

Model 2

Model 4

Model 5

Energy
Hadronic Interactions from TeV to meV

TeV hadron

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

~100 MeV to thermal

~10 MeV to thermal

~ GeV - ~100 MeV

~100 MeV - ~10 MeV
Hadron Elastic Scattering

- **GHEISHA-style (G4LElastic)**
  - classical scattering (not all relativistic)
  - simple parameterization of cross section, angular distribution
  - can be used for all long-lived hadron projectiles, all energies

- **Coherent elastic**
  - G4LEpp for (p,p), (n,n) : taken from detailed phase-shift analysis, good up to 1.2 GeV
  - G4LEnp for (n,p) : same as above
  - G4HadronElastic for (h,A) : nuclear model details included as well as interference effects, good for 1 GeV and above, all long-lived hadrons
Elastic Scattering Validation (G4LElastic)
Precompound Models (1)

- **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, 3He, alpha
  - once equilibrium state is reached, four other models are called to take care of nuclear evaporation and breakup
    - **these models not currently callable by users**
- **The parameterized and cascade models all have nuclear de-excitation models embedded in them**
Precompound Models (2)

• **Invocation of Precompound model:**

  - G4ExcitationHandler* theHandler = new G4ExcitationHandler;
    G4PrecompoundModel* preModel =
    new G4PrecompoundModel(theHandler);

  // Create equilibrium decay models and assign to Precompound model

  nProc->RegisterMe(preModel);
  neutronManager->AddDiscreteProcess(nProc);

  // Register model to process, process to particle
Bertini Cascade Model

• **The Bertini model is a classical cascade:**
  − it is a solution to the Boltzmann equation on average
  − no scattering matrix calculated
  − can be traced back to some of the earliest codes (1960s)

• **Core code:**
  − elementary particle collider: uses free-space cross sections to generate secondaries
  − cascade in nuclear medium
  − pre-equilibrium and equilibrium decay of residual nucleus
  − detailed 3-D model of nucleus
Bertini Cascade (Comic Book Version)
Bertini Cascade (text version)

- **Modeling sequence:**
  - incident particle penetrates nucleus, is propagated in a density-dependent nuclear potential
  - all hadron-nucleon interactions based on free-space cross sections, angular distributions, but no interaction if Pauli exclusion not obeyed
  - each secondary from initial interaction is propagated in nuclear potential until it interacts or leaves nucleus
  - during the cascade, particle-hole exciton states are collected
  - pre-equilibrium decay occurs using exciton states
  - next, nuclear breakup, evaporation, or fission models
Using the Bertini Cascade

• In Geant4 the Bertini model is currently used for p, n, π⁺, π⁻, K⁺, K⁻, K⁰_L, K⁰_S, Λ, Σ⁰, Σ⁺, Σ⁻, Ξ⁰, Ξ⁻
  - valid for incident energies of 0 – 10 GeV
  - soon to be extended to 12 - 15 GeV

• Invocation sequence

  - G4CascadeInterface* bertini = new G4CascadeInterface();
  G4ProtonInelasticProcess* pproc =
    new G4ProtonInelasticProcess();
  pproc -> RegisterMe(bertini);
  proton_manager -> AddDiscreteProcess(pproc);
Validation of the Bertini Cascade
Binary Cascade

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

• In Geant4 the Binary cascade model is currently used for incident p, n and $\pi$
  − valid for incident p, n from 0 to 10 GeV
  − valid for incident $\pi^+$, $\pi^-$ from 0 to 1.3 GeV

• A variant of the model, G4BinaryLightIonReaction, is valid for incident ions up to $A = 12$ (or higher if target has $A < 12$)
Using the Binary Cascade

• **Invocation sequence Binary cascade**
  
  - G4BinaryCascade* binary = new G4BinaryCascade();
    G4PionPlusInelasticProcess* pproc = new
    G4PionPlusInelasticProcess();
    
    pproc -> RegisterMe(binary);
    piplus_manager -> AddDiscreteProcess(pproc);

• **Invocation sequence BinaryLightIonReaction**
  
  - G4BinaryLightIonReaction* ionBinary = new
    G4BinaryLightIonReaction;
    
    ionProc->RegisterMe(ionBinary);
    genericIonManager->AddDiscreteProcess(ionProc);
Validation of the Binary Cascade
256 MeV protons

![Graph showing neutron yield at 7.5° for different materials: Be, Al, Fe, Pb. The graph plots dσ/dE₅Ω [mb/MeV/sr] vs. E₅ [MeV].]
LEP, HEP (Comic Book Version)

CM Frame
LEP, HEP models (text version)

- Modeling sequence:
  - initial interaction of hadron with nucleon in nucleus
  - highly excited hadron is fragmented into more hadrons
  - particles from initial interaction divided into forward and backward clusters in CM
  - another cluster of backward going nucleons added to account for intra-nuclear cascade
  - clusters are decayed into pions and nucleons
  - remnant nucleus is de-excited by emission of p, n, d, t, alpha
Using the LEP and HEP models

- The LEP and HEP models are valid for p, n, π, K, Λ, Σ, Ξ, Ω, d, t, α
  - LEP valid for incident energies of 0 – ~30 GeV
  - HEP valid for incident energies of ~20 GeV – 15 TeV
- Invocation sequence
  - G4ProtonInelasticProcess* pproc = new G4ProtonInelasticProcess();
  - G4LEProtonInelastic* LEproton = new G4LEProtonInelastic();
  - pproc -> RegisterMe(LEproton);
  - G4HEProtonInelastic* HEproton = new G4HEProtonInelastic();
  - HEproton -> SetMinEnergy(25*GeV);
  - pproc -> RegisterMe(HEproton);
  - proton_manager -> AddDiscreteProcess(pproc);
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

• Two main types of elastic scattering are available:
  − GHEISHA-style
  − coherent

• Precompound models are available for low energy nucleon projectiles and nuclear de-excitation
Summary (2)

- Cascade models (Bertini, Binary, INCL/ABLA) are valid for fewer particles over a smaller energy range
  - more theory-based
  - more detailed
  - slower

- Parameterized models (LEP, HEP) handle the most particle types over the largest energy range
  - based on fits to data and some theory
  - not very detailed
  - fast