Hadronic Physics I

Geant4 Tutorial at Jefferson Lab
11 July 2012
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Outline

• Overview of hadronic physics
  • processes, cross sections, models
  • hadronic framework and organization
• Elastic scattering
• Neutron physics
• Ion physics
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.
particle

- process 1 at rest
- process 2 in-flight
- process 2
- process n

- model 1
- model 2
- ... model n

Energy range manager

- c.s. set 1
- c.s. set 2
- ... c.s. set n

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 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

Energy

Set 1
Set 2
Set 3
Set 4

Default cross section set
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
Parameterized Hadronic Models

• Depend mostly on fits to data with some theoretical guidance

• Two such models available:
  • Low Energy Parameterized (LEP) for $E < 20$ GeV
  • High Energy Parameterized (HEP) for $E > 20$ GeV
  • each type refers to a collection of models (one for each hadron type)

• Both LEP and HEP are re-engineered versions of the Fortran Gheisha code used in Geant3

• Code is fast and applies to all particle types, but is not particularly detailed
  • eventually will be phased out
Partial Hadronic Model Inventory

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

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

Model returned by GetHadronicInteraction()

1 1 + 3 3 Error 2 Error 2

Model 1 Model 3 Error 2

Model 3 Model 4 Error 2

Model 1 Model 2

Energy
Hadronic Model Organization

- process
  - at rest
  - discrete (in-flight)
    - models
      - theory framework
        - high energy
          - parton-string
            - string fragmentation
        - spallation framework
          - precompound
            - cascade
          - propagate
          - evaporation
Hadronic Interactions from TeV to meV

- TeV hadron
- $dE/dx \sim A^{1/3}\text{GeV}$
- $\sim\text{GeV}$ to $\sim\text{100 MeV}$
- $p, n, d, t, \alpha$
- $\sim\text{100 MeV}$ to $\sim\text{10 MeV}$
- $\gamma$ and $n$
- $\sim\text{10 MeV}$ to thermal
Hadron Elastic Scattering

• G4WHadronElasticProcess: general elastic scattering
  • valid for all energies
  • valid for p, n, π, K, hyperons, anti-nucleons, anti-hyperons
  • based in part on old Gheisha code, but with relativistic corrections

• Coherent elastic
  • G4LEpp for (p,p), (n,n) : taken from SAID phase shift analysis, good up to 1.2 GeV
  • G4LEnp for (n,p) : same as above
  • G4HadronElastic for general hadron-nucleus scattering

• Neutron elastic
  • high precision (HP) model uses data from ENDF (E < 20 MeV)
Elastic Scattering Validation (G4HadronElastic)
Low Energy Neutron Physics

• Below 20 MeV incident energy, Geant4 provides several models for treating neutron interactions in detail

• The high precision models (NeutronHP) are data-driven and depend on a large database of cross sections, etc.
  • the G4NDL database is available for download from the Geant4 web site
  • elastic, inelastic, capture and fission models all use this isotope-dependent data

• There are also models to handle thermal scattering from chemically bound atoms
Geant4 Neutron Data Library (G4NDL)

• Contains the data files for the high precision neutron models
  • includes both cross sections and final states

• From Geant4 9.5 onward, G4NDL is based solely on the ENDF/B-VII database
  • G4NDL format is now identical to that of ENDF/B-VII
  • use G4NDL 4.0 or later

• Prior to G4 9.5 G4NDL selected data from 9 different databases, each with its own format
  • Brond-2.1, CENDL2.2, EFF-3, ENDF/B-VI, FENDL/E2.0, JEF2.2, JENDL-FF, JENDL-3 and MENDL-2
  • G4NDL also had its own (undocumented) format
G4NeutronHPElastic

• Handles elastic scattering of neutrons by sampling differential cross section data
  • interpolates between points in the cross section tables as a function of energy
  • also interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
  • scattered neutron and recoil nucleus generated as final state

• Note that because look-up tables are based on binned data, there will always be a small energy non-conservation
  • true for inelastic, capture and fission processes as well
G4NeutronHPInelastic

- Currently supports 34 inelastic final states + n gamma (discrete and continuum)
  - n (A,Z) -> (A-1, Z-1) n p
  - n (A,Z) -> (A-3, Z) n n n n
  - n (A,Z) -> (A-4, Z-2) d t
  - ........

- Secondary distribution probabilities
  - isotropic emission
  - discrete two-body kinematics
  - N-body phase space
  - continuum energy-angle distributions (in lab and CM)
Neutron Inelastic: $^{154}$Gd (n,2n) Comparison to Data
G4NeutronHPCapture

• Neutron capture on a nucleus produces photons described by either
  • the number of photons (multiplicity), or
  • photon production cross sections

• Photon spectra are either
  • discrete emission, using either cross sections or multiplicities from data libraries, or
  • continuous, with the spectrum calculated according to tabulated parameters
    • $f(E\rightarrow E_\gamma) = \sum_i p_i(E) g_i(E\rightarrow E_\gamma)$
    where $p_i$ and $g_i$ come from the libraries
High Precision Neutrons
Comparing Geant4 and MCNPX

Comparing G4 HP old & new with MCNPX
G4NeutronHPFission

• Currently only uranium fission data are available in Geant4

• First chance, second chance, third chance and fourth chance fission taken into account

• Resulting neutron energy distributions are implemented in different ways
  • as a function of incoming and outgoing neutron energy
  • as a Maxwell spectrum
  • evaporation spectrum
  • energy-dependent Watt spectrum
  • Madland-Nix spectrum
Including HP Neutrons in Your Physics List

- Elastic scattering
  
  \[
  \text{G4HadronElasticProcess}^* \ \text{theNEP} = \text{new G4HadronElasticProcess};
  \]

  // the cross sections

  \[
  \text{G4NeutronHPElasticData}^* \ \text{theNEData} = \text{new G4NeutronHPElasticData};
  \]

  \[
  \text{theNEP} \text{-} \text{AddDataSet} (\text{theNEData});
  \]

  // the model

  \[
  \text{G4NeutronHPElastic}^* \ \text{theNEM} = \text{new G4NeutronHPElastic};
  \]

  \[
  \text{theNEP} \text{-} \text{RegisterMe} (\text{theNEM});
  \]

  \[
  \text{neutManager} \text{-} \text{AddDiscreteProcess} (\text{theNEP});
  \]
G4NeutronHPorLE Models

• The high precision neutron models do not cover all elements/isotopes
  - often no data: latest G4NDL has 395 isotopes, but there are thousands
  - data may exist but not yet be evaluated
• A Geant4 application must have a model under all circumstances, otherwise a fatal error occurs
• G4NeutronHPorLE models were developed to solve this problem
  - HPorLE models call the HP models if data exists
  - if no data, the Low Energy Parameterized (GHEISHA-style) model is called
  - elastic, inelastic, capture and fission provided
Thermal Neutron Scattering from Chemically Bound Atoms

- At thermal energies, atomic motion, vibration, rotation of bound atoms affect neutron scattering cross sections and the angular distribution of secondary neutrons.

- The energy loss (or gain) of such scattered neutrons may be different from those from interactions with unbound atoms.

- Original HP models included only individual Maxwellian motion of target nucleus (free gas model).

- New behavior handled by model and cross section classes:
  - G4HPThermalScatteringData, and
  - G4HPThermalScattering.
Ion-Ion Inelastic Scattering

• Up to now we’ve considered only hadron-nucleus interactions, but Geant4 has five different nucleus-nucleus collision models
  • G4BinaryLightIon
  • G4WilsonAbrasion/G4WilsonAblation
  • G4EMDissociationModel
  • G4QMD
  • G4Incl

• Also provided are several ion-ion cross section data sets
• Currently no ion-ion elastic scattering models provided
G4BinaryLightIonReaction

• This model is an extension of the G4BinaryCascade model (to be discussed later)

• The hadron-nuclear interaction part is identical, but the nucleus-nucleus part involves:
  • preparation of two 3D nuclei with Woods-Saxon or harmonic oscillator potentials
  • lighter nucleus is always assumed to be the projectile
  • nucleons in the projectile are entered with their positions and momenta into the initial collision state
  • nucleons are interacted one-by-one with the target nucleus, using the original Binary cascade model
G4WilsonAbrasion and G4WilsonAblation

• A simplified macroscopic model of nucleus-nucleus collisions
  • based largely on geometric arguments
  • faster than Binary cascade or QMD models, but less detailed

• The two models are used together
  • G4WilsonAbrasion handles the initial collision in which a chunk of the target nucleus is gouged out by the projectile nucleus
  • G4WilsonAblation handles the de-excitation of the resulting fragments

• Based on the NUCFRG2 model (NASA TP 3533)
• Can be used up to 10 GeV/n
Wilson Abrasion/Ablation
G4EMDissociation Model

• Electromagnetic dissociation is the liberation of nucleons or nuclear fragments as a result of strong EM fields
  • as when two high-Z nuclei approach
  • exchange of virtual photons instead of nuclear force

• Useful for relativistic nucleus-nucleus collisions where the Z of the nucleus is large

• Model and cross sections are an implementation of the NUCFRG2 model (NASA TP 3533)
• Can be used up to 100 TeV
INCL Nucleus-Nucleus

• INCL hadron-nucleus model used to interact projectile nucleons with target
• True potential is not used for projectile nucleus, but binding energy is taken into account
• True potential is used for target
• Projectile nucleons can pass through to form fragment or interact with nucleus
G4QMD Model

- BinaryLightIonReaction has some limitations
  - neglects participant-participant scattering
  - uses simple time-independent nuclear potential
  - imposes small A limitation for target or projectile
  - Binary cascade base model can only go to 5-10 GeV

- Solution is QMD (quantum molecular dynamics) model
  - an extension of the classical molecular dynamics model
  - treats each nucleon as a gaussian wave packet
  - propagation with scattering which takes Pauli principal into account
  - can be used for high energy, high Z collisions
QMD Validation
Ar40 560MeV/n on Lead

+ Data
+ G4BinaryCascade
+ G4QMD
180MeV Proton on Al

Fragment A=7

Cross section [mb/MeV/sr] vs. fragment energy [MeV]
Including QMD in Your Physics List

- G4HadronInelasticProcess* ionInel =
  new G4HadronInelasticProcess(“ionInelastic”,
  G4GenericIon::G4GenericIon());

// the cross sections
G4TripathiCrossSection* tripCS = new G4TripathiCrossSection;
G4IonsShenCrossSection* shenCS = new G4IonsShenCrossSection;
ionInel->AddDataSet(shenCS);
ionInel->AddDataSet(tripCS);

// assign model to process
G4QMDReaction* theQMD = new G4QMDReaction;
ionInel->RegisterMe(theQMD);
G4ProcessManager* pman = G4GenericIon::G4GenericIon()->
  GetProcessManager();
pman->AddDiscreteProcess(ionInel);
Ion-ion Cross Sections

• Cross section data sets available from 10 MeV/N to 10 GeV/N
  • Tripathi, TripathiLight (for light nuclei)
  • Kox
  • Shen
  • Sihver

• These are empirical and parameterized cross section formulae with some theoretical insight
• G4GeneralSpaceNNCrossSection was prepared to assist users in selecting the appropriate cross section formula
Summary

• Geant4 hadronic physics is organized according to processes, models and cross sections
  • user builds process by adding models and cross sections to it
• Many processes, models, cross sections to choose from
  • cover energy range from sub-thermal to multi-TeV

• One elastic scattering process for all particle types
• Specialized high precision neutron models
  • Geant4 neutron data library now follows ENDF/B-VII format
• Several models for ion-ion collisions
  • Wilson models fast, but not so detailed
  • QMD model detailed but not so fast