Hadronic Physics II

Geant4 Tutorial at Lund University

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Outline

• Elastic processes and models

• Low energy neutron and proton physics

• Ion-ion physics

• Capture, stopping and fission reactions
Hadron Elastic Scattering

- G4HadronElasticProcess: general elastic scattering
  - valid for all energies, all projectiles
  - includes p, n, π, K, hyperons, anti-nucleons, anti-hyperons, ...
  - uses proton cut values (scaled by Z) for recoil nucleus generation

- Implemented by
  - elastic cross section data sets
  - elastic models
Hadron Elastic Cross Sections

- G4HadronElasticDataSet (from Geant4/Gheisha)

- G4ComponentAntiNuclNuclearXS
  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach

- G4BGGPionElasticXS
  - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above

- G4ChipsNeutron(Proton)ElasticXS
  - elastic cross sections extracted from CHIPS framework
Hadronic Models Implementing G4HadronElasticProcess

- p, n
- π
- K
- anti- (p, α, d, t, 3He)
- Y, anti-Y, anti-n, α, d, t

Energy Range:
- 0 MeV
- 100 MeV
- 1 GeV
Elastic Scattering Validation (G4HadronElastic)
G4ElasticHadrNucleusHE (1 GeV p on C)
Low Energy Hadron Physics

• Below 20 MeV incident energy, Geant4 provides several models for treating n, p, d, t, $^3$He and $\alpha$ interactions in detail.

• The high precision models (ParticleHP) 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
  • TENDL optional database is also available
  • elastic, inelastic, capture and fission models all use this isotope-dependent data

• There are also models to handle thermal scattering from chemically bound atoms
High Precision Particles

• ParticleHP models provide elastic, inelastic, capture and fission for incident n, p, d, t, \(^3\)He, \(\alpha\)
  • mostly below 20 MeV for n
  • \(0 < E < 200\) MeV for charged
  • also depends on large database (ENDF)
  • alternative dbs ready: TENDL, IAEA medical, IBANDL
  • recently merged with NeutronHP

• Code currently available
  • good comparisons so far with MCNP
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 data is now taken only from ENDF/B-VII, but still has G4NDL format
  • 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
G4ParticleHPElastic

• Handles elastic scattering of n, p, d, t, $^3\text{He}$, $\alpha$ 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 particle 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
G4ParticleHPInelastic

• Currently supports many inelastic final states + n gamma (discrete and continuum)
  • n \( (A,Z) \rightarrow (A-1, Z-1) \) n p
  • n \( (A,Z) \rightarrow (A-3, Z) \) n n n n
  • n \( (A,Z) \rightarrow (A-4, Z-2) \) 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
LEND – the new Livermore Neutron Models

• An alternative to the HP models
  • better code design
  • faster
  • Livermore database not yet as extensive G4NDL

• Corresponding model for each model in HP
  • elastic, inelastic, capture, fission

• Invocation in physics list:
  • use model names G4LENDElastic, G4LENDInelastic, G4LENDCapture, G4LENDFission, and cross sections G4LENDElasticCrossSection, G4LENDInelasticCrossSection, G4LENDCaptureCrossSection, G4LENDFissionCrossSection

• Database to use: go to ftp://gdo-nuclear.ucllnl.org/pub/ and select G4LEND, then ENDF-B-VII.0.tar.gz
Ion-Ion Inelastic Scattering

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

• 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]

- exp 20°
- exp 40°
- exp 70°
- G4BC 20°
- G4BC 40°
- G4BC 70°
- G4QMD 20°
- G4QMD 40°
- G4QMD 70°
Nucleus-nucleus 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
Nucleus-nucleus Cross Sections

• G4ComponentGGNuclNuclXsc
  • total, inelastic and elastic nucleus-nucleus cross sections using Glauber model with Gribov corrections

• G4ComponentAntiNuclNucleusXS
  • total, inelastic and elastic cross sections for anti-nucleon and anti-nucleus nucleus scattering
Capture and Stopping Models

Capture

Stopping

\( n \)

\( \gamma \) s and nucleons

negative particle

atomic cascade

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
g4/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
Summary (1)

• All hadron elastic scattering is handled by one process
  • but implemented by several models depending on energy and particle type

• Specialized high precision models (n, p, d, t, \( ^3 \text{He} \), \( \alpha \) )
  • HP models which use G4NDL, now based entirely on ENDF/B-VII
  • alternative LEND (Livermore) models are faster but currently less extensive – use the ENDF.B-VII library

• Several models for nucleus-nucleus collisions
  • Wilson models fast, but not so detailed
  • Cascade models more detailed but slower
  • QMD model very detailed but not so fast
Summary (2)

• Capture, stopping processes for selected particle types

• Several fission models available
  • some implicitly included in other models
  • some must be explicitly added by users
  • make sure not to double-count!