Geant4 10.4

Hadronic Physics II

Geant4 Tutorial at Lund University

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Dennis Wright

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Elastic processes and models
- Low energy neutron and proton physics
- Ion-ion physics
- Capture, stopping and fission reactions

Hadron Elastic Scattering

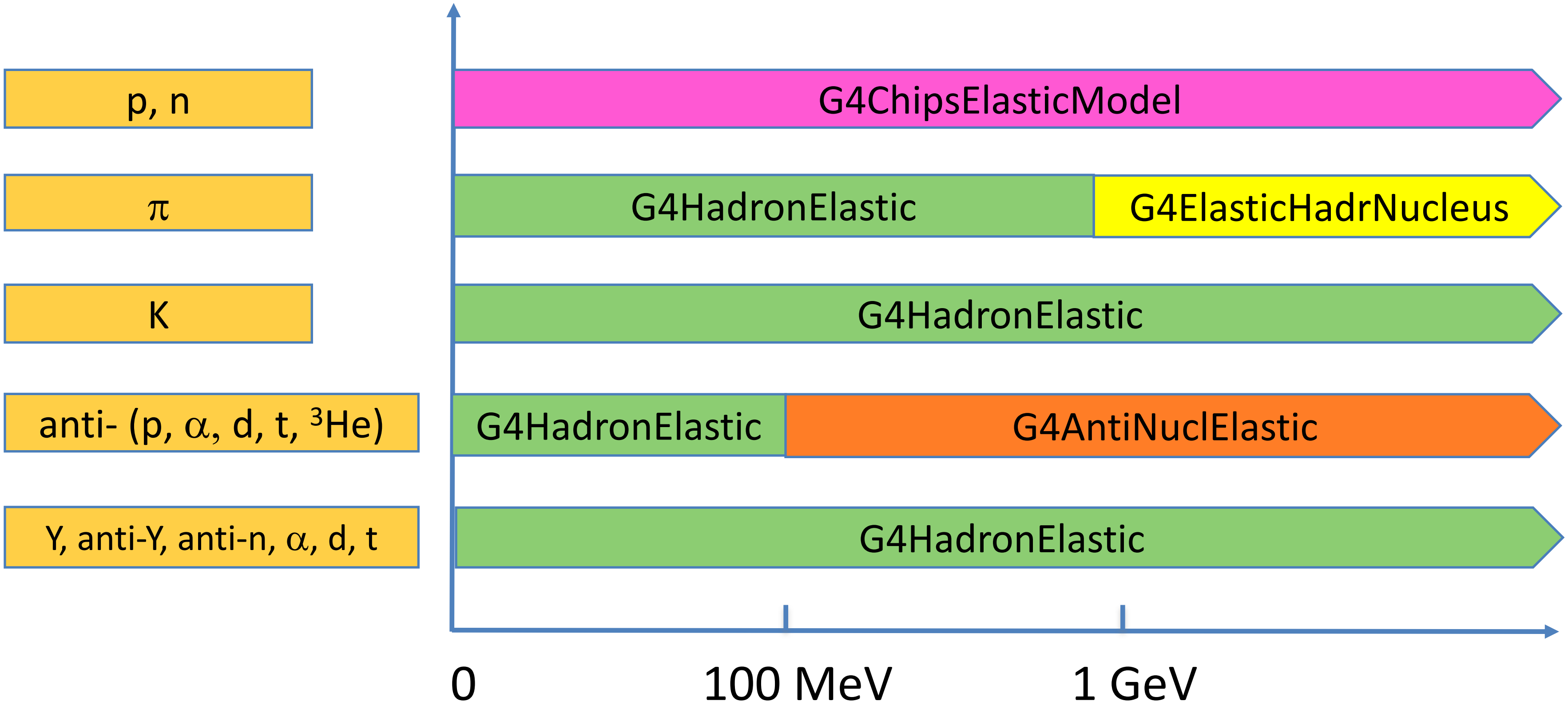
- G4HadronElasticProcess: general elastic scattering
  - valid for all energies, all projectiles
  - includes p, n, π , K, hyperons, anti-nucleons, anti-hyperons, …
  - uses proton cut values (scaled by Z) for recoil nucleus generation

- Implemented by
  - elastic cross section data sets
  - elastic models

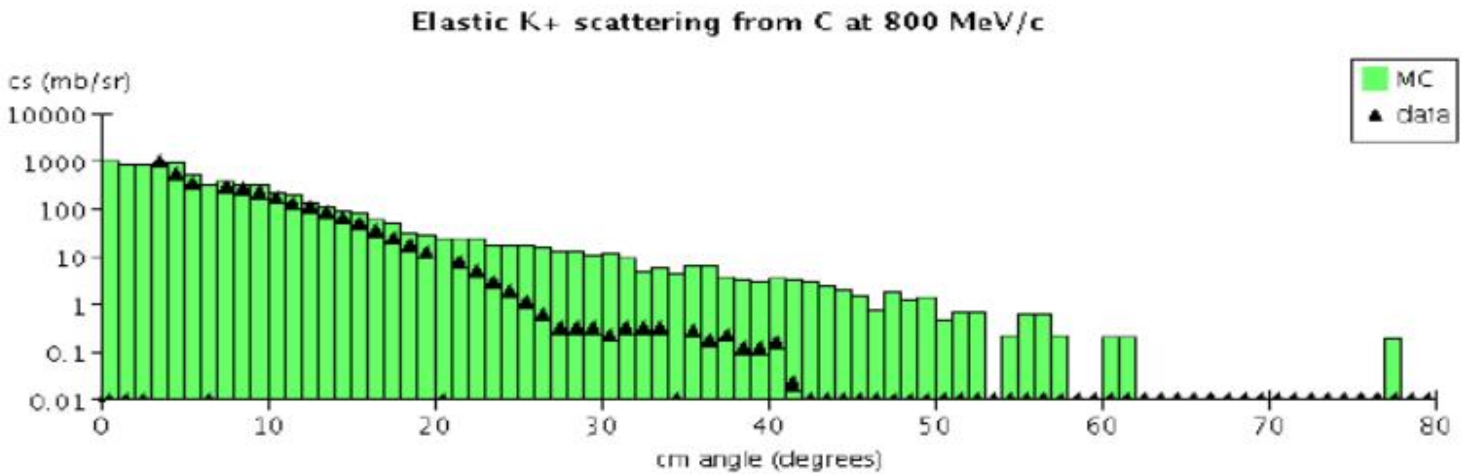
Hadron Elastic Cross Sections

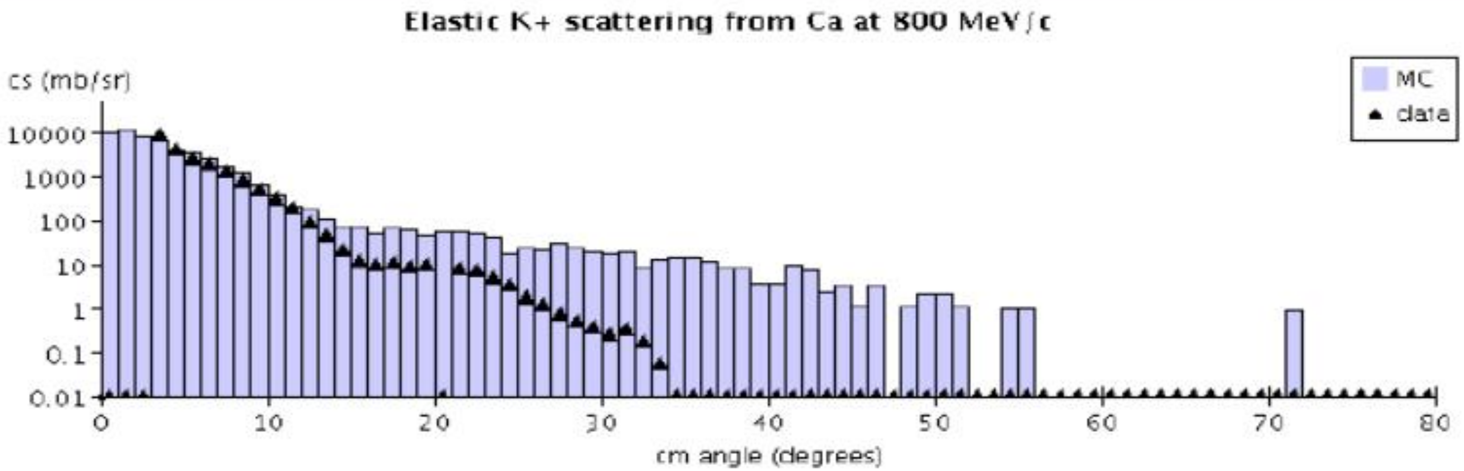
- G4HadronElasticDataSet (from Geant4/Gheisha)
- G4ComponentAntiNuclNuclearXS
  - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach
- G4BGGPionElasticXS
  - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above
- G4ChipsNeutron(Proton)ElasticXS
  - elastic cross sections extracted from CHIPS framework

Hadronic Models Implementing G4HadronElasticProcess

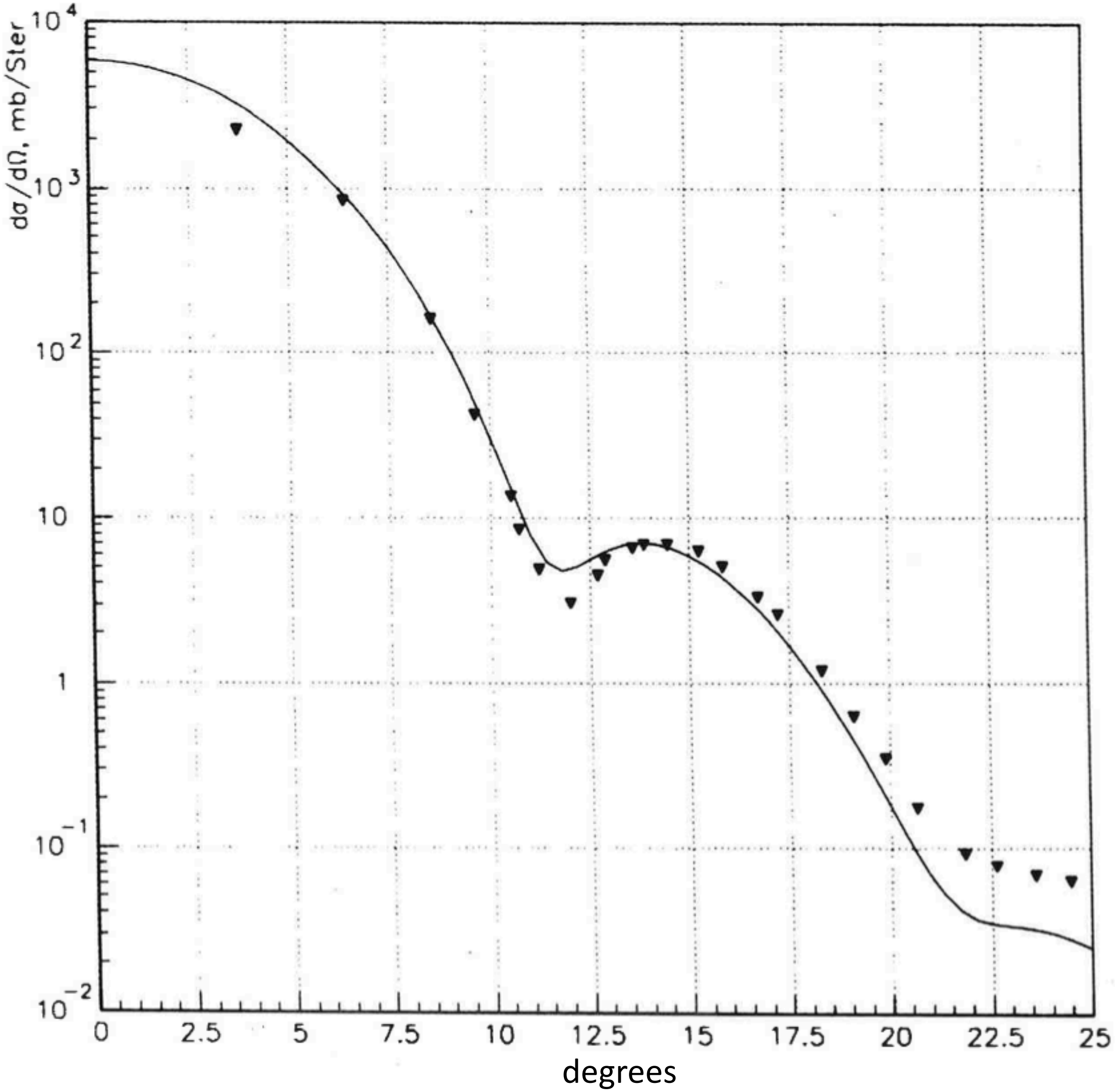


Elastic Scattering Validation (G4HadronElastic)





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 α 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, α
  - 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

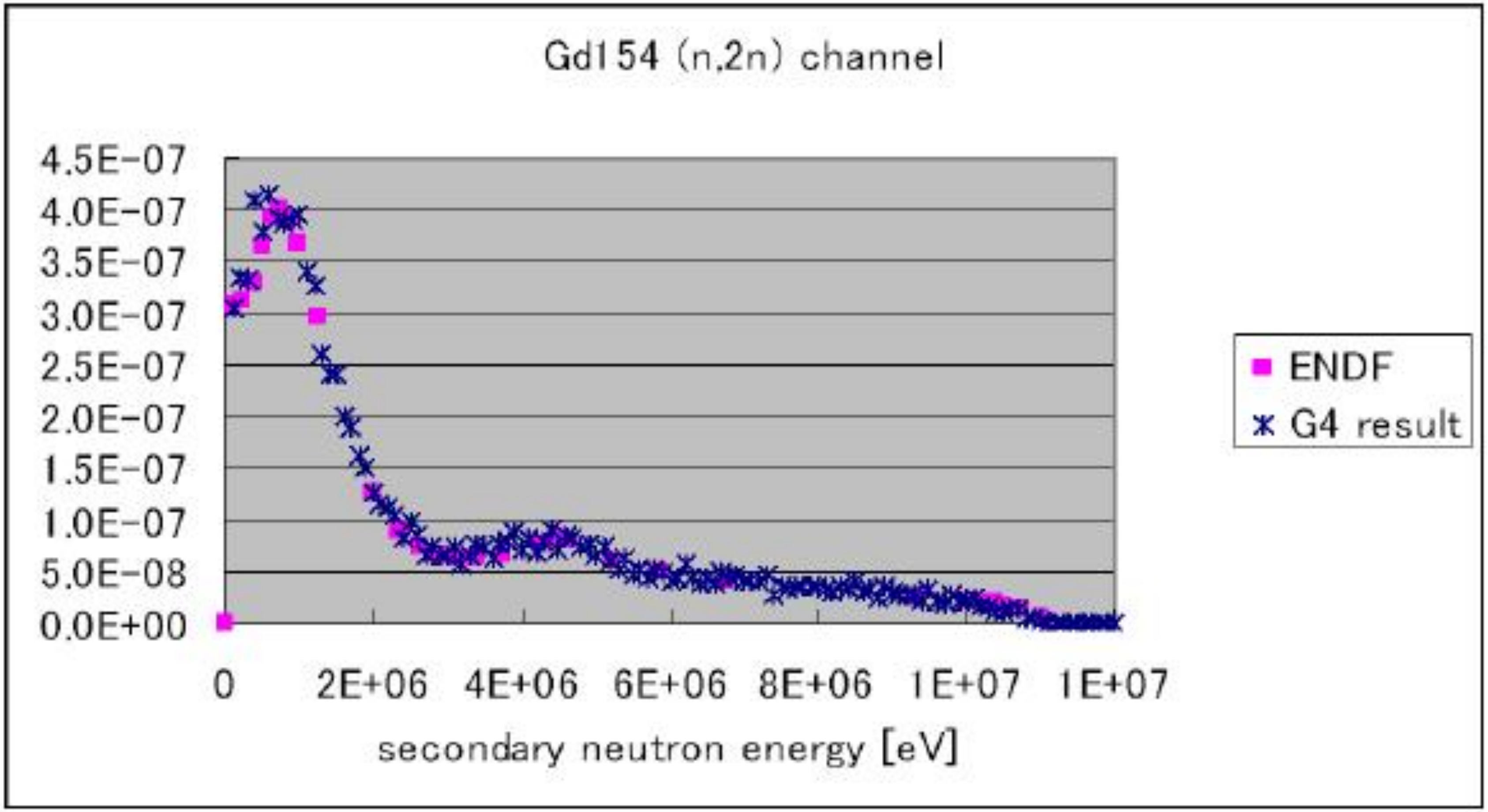
- Handles elastic scattering of n, p, d, t, ^{3}He, α by sampling differential cross section data
  - interpolates between points in the cross section tables as a function of energy
  - also interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
  - 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) -> (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



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

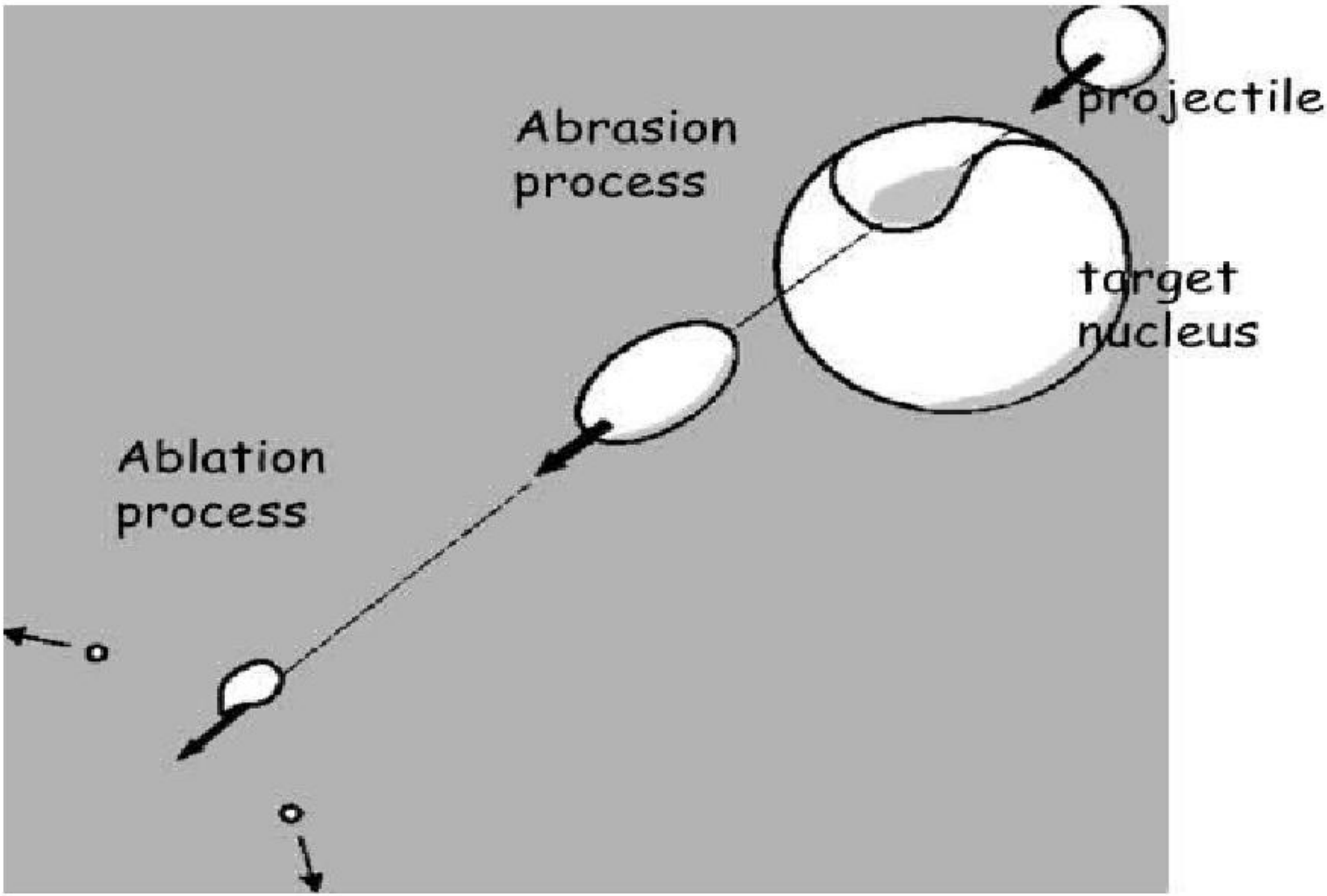
- This model is an extension of the G4BinaryCascade model (to be discussed later)

- 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

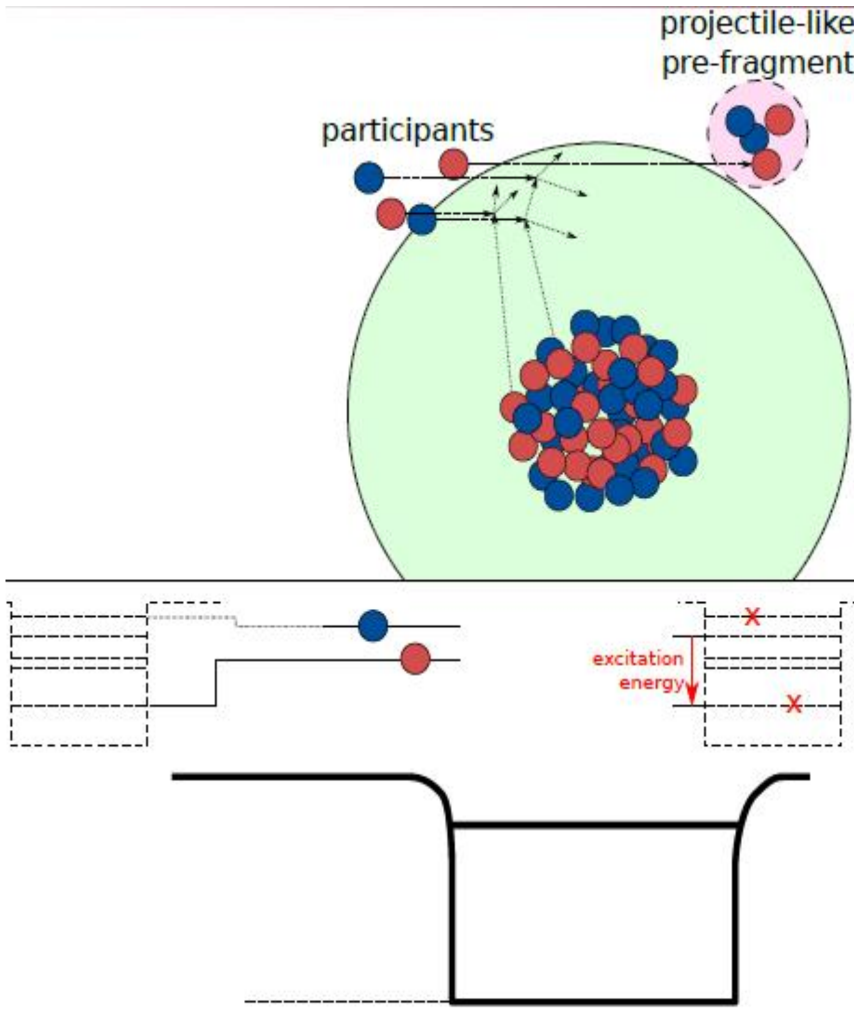
- Electromagnetic dissociation is the liberation of nucleons or nuclear fragments as a result of strong EM fields
  - as when two high-Z nuclei approach
  - exchange of virtual photons instead of nuclear force

- 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



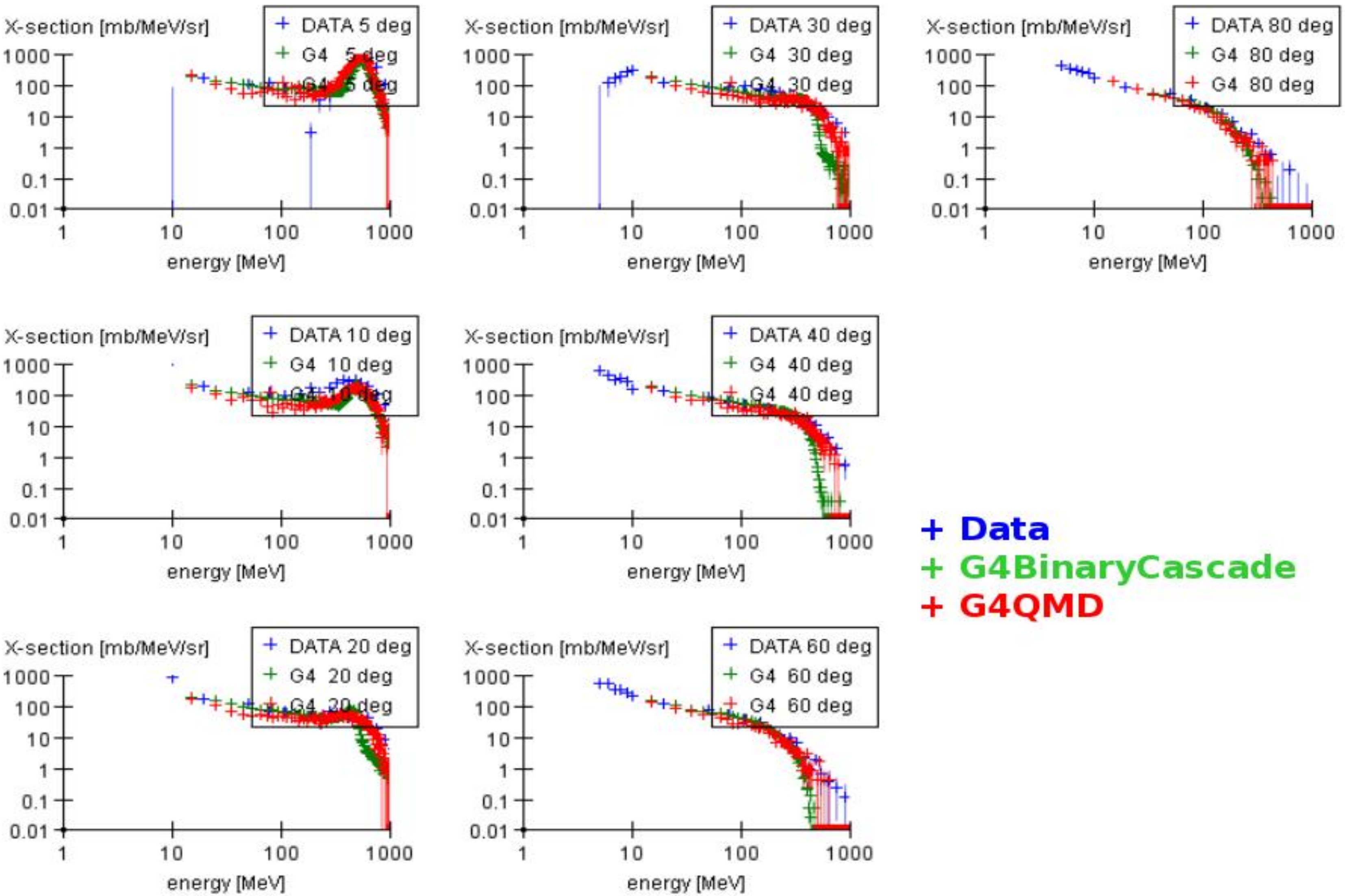
G4QMD Model

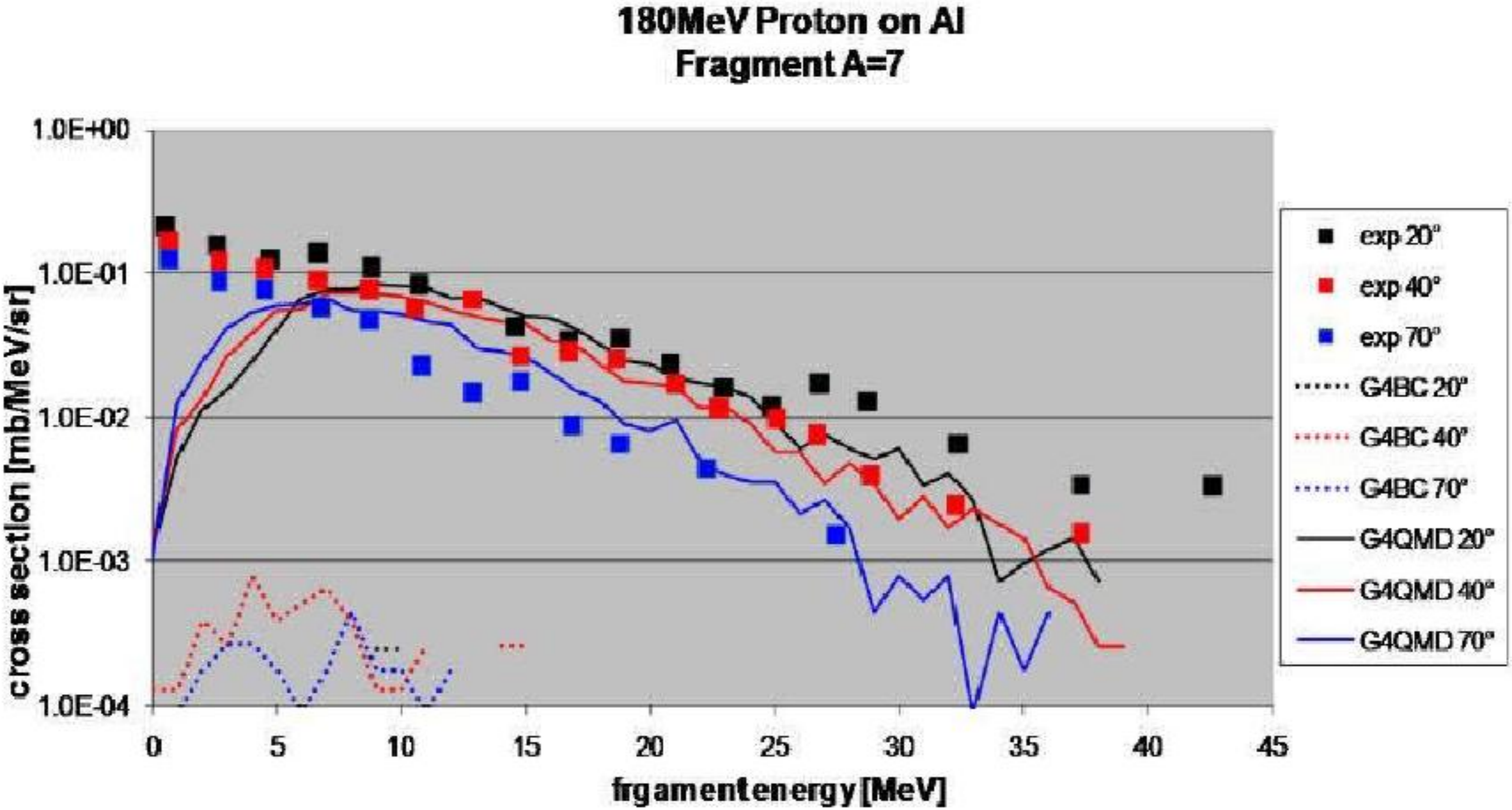
- BinaryLightIonReaction has some limitations
  - neglects participant-participant scattering
  - uses simple time-independent nuclear potential
  - imposes small A limitation for target or projectile
  - Binary cascade base model can only go to 5-10 GeV

- 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




180MeV Proton on Al
Fragment A=7
cross section [mb/MeV/sr]
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
0
5
10
15
20
25
30
35
40
45
frgament 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

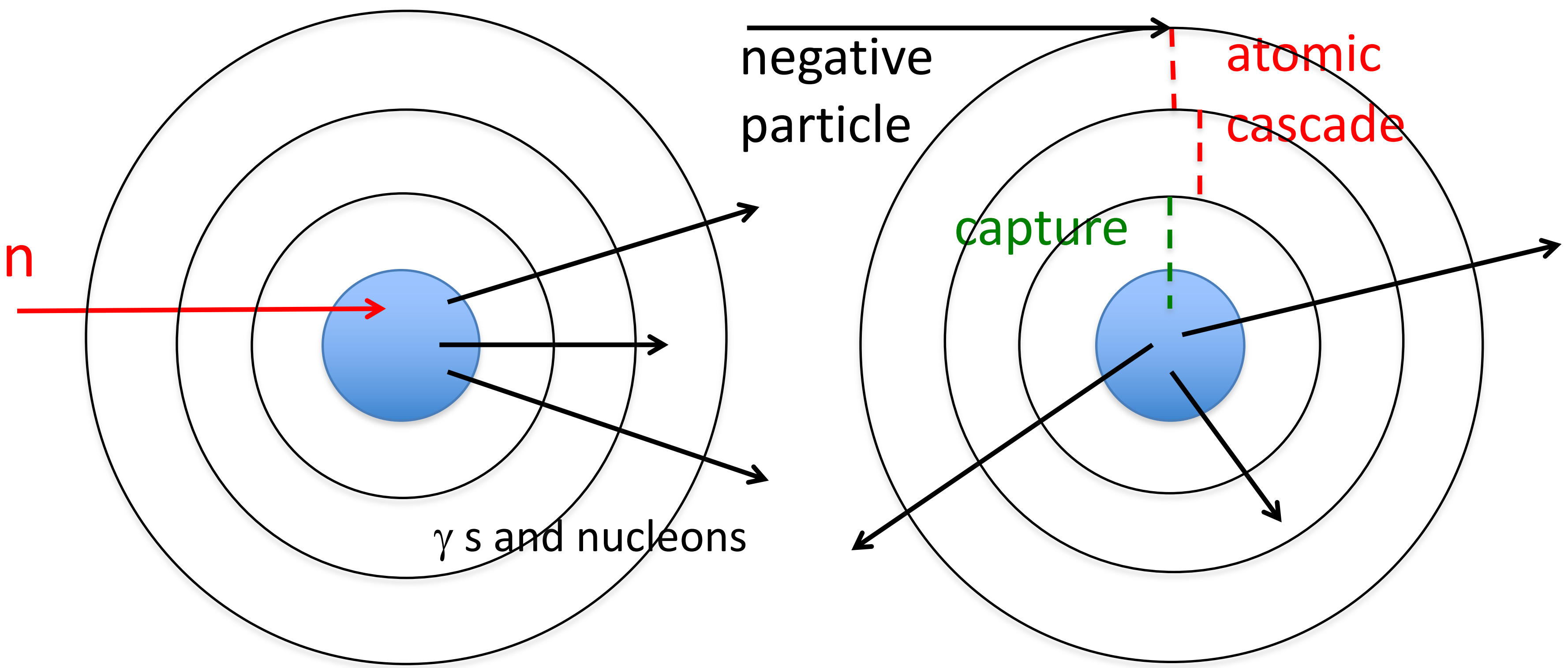
- G4ComponentGGNuclNuclXsc
  - total, inelastic and elastic nucleus-nucleus cross sections using Glauber model with Gribov corrections

- G4ComponentAntiNuclNucleusXS
  - total, inelastic and elastic cross sections for anti-nucleon and anti-nucleus nucleus scattering

Capture and Stopping Models

Capture

Stopping



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

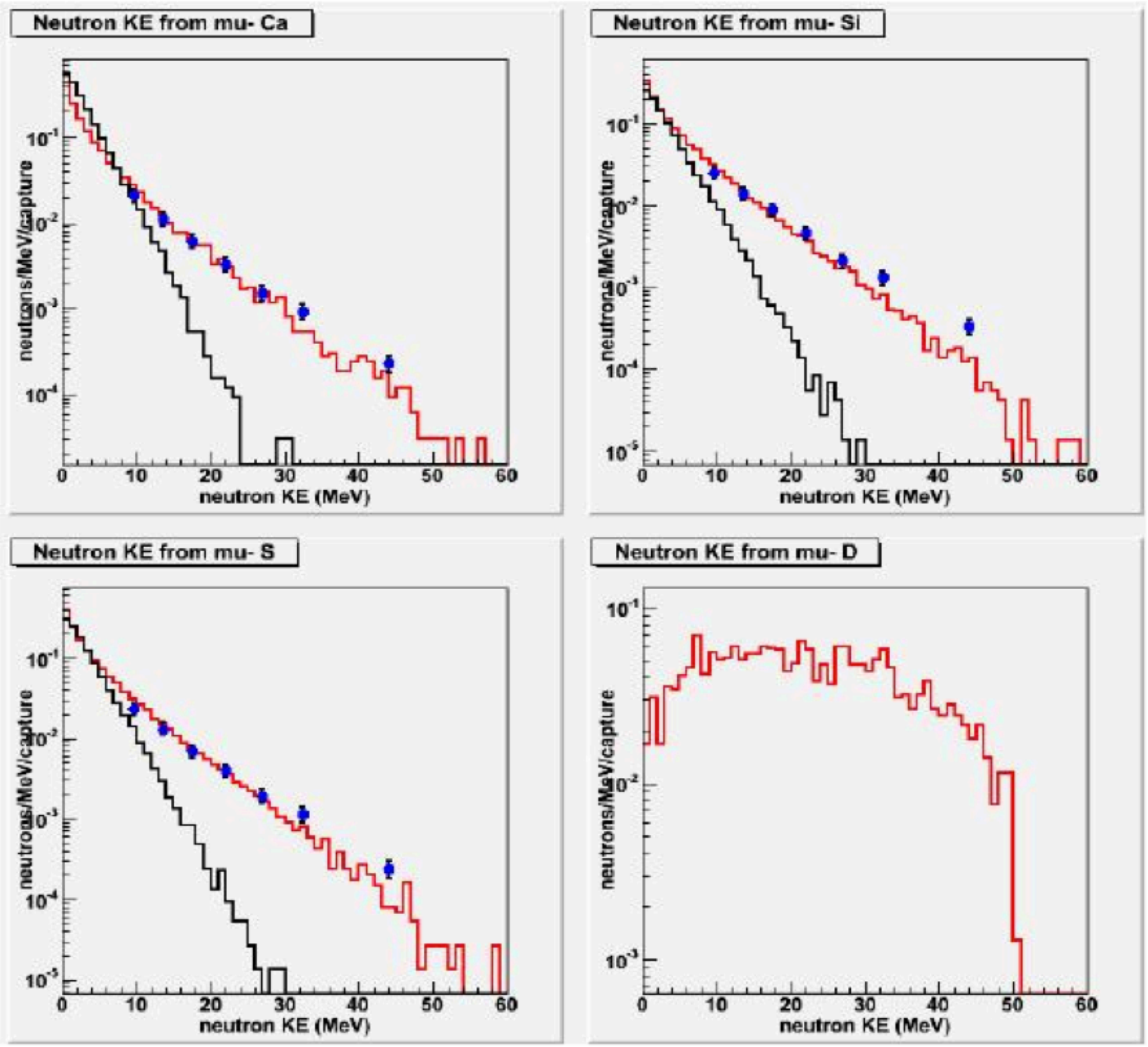
- G4AntiProtonAbsorptionFritiof, G4AntiSigmaPlusAbsorptionFritiof
  - FTF model used because > 2 GeV available in reaction
  - G4Precompound model used for de-excitation of nucleus
  - includes atomic cascade but not decay in orbit

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

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}He, α)
  - 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 !