Hadronic Physics 2

Cours Geant4 @ Paris 2007

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Ministère de la Recherche,

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Gunter Folger

Overview

- Low Energy Neutron Physics
  - High Precision Neutron Models
- Ion Physics
  - Inelastic
  - Electromagnetic Dissociation
  - Radio Active Decay

Acknowledgement:
Slides are a close copy of slides prepared by T.Koi for Geant4 course held at SLAC, May 2007

Low energy (< 20MeV) neutrons physics

- High Precision Neutron Models (and Cross Section Data Sets)
  - G4NDL
    - ENDF
  - Elastic
  - Inelastic
  - Capture
  - Fission
- NeutronHPorLEModel(s)
- ThermalScatteringModels (and Cross Section data Sets)
- JENDL High Energy Files (cross sections < 3GeV)

G4NDL
(Geant4 Neutron Data Library)

- The neutron data files for High Precision Neutron models
- The data are including both cross sections and final states.
- The data are derived evaluations based on the following evaluated data libraries (in alphabetic order)
  - Brond-2.1
  - CENDL2.2
  - EFF-3
  - ENDF/B-VI.0, 1, 4
  - FENDL/E2.0
  - JEF2.2
  - JENDL-FF
  - JENDL-3.1,2
  - MENDL-2
- The data format is similar ENDF, however it is not equal to.

Evaluated Nuclear Data File-6

- "ENDF" is used in two meanings
- One is Data Formats and Procedures
  - How to write Nuclear Data files
  - How to use the Nuclear Data files
- The other is name of recommended libraries of USA nuclear data projects.
  - ENDF/B-VI.8
    - 313 isotopes including 5 isomers
    - 15 elements
  - ENDF/B-VII.0
    - Released on 2006 Dec
    - almost 400 isotopes
    - not yet migrated
- After G4NDL3.8 (3.10 is latest) we concentrated translation from ENDF library.
  - No more evaluation by ourselves.

G4NeutronHPElastic

- The final state of elastic scattering is described by sampling the differential scattering cross-sections
  - tabulation of the differential cross-section $$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\cos\theta, E)$$
  - a series of legendre polynomials and the legendre coefficients

$$\frac{2\pi}{\sigma(E)}\frac{d\sigma}{d\Omega}(\cos\theta, E) = \sum_{l=0}^{n_l}\frac{2l+1}{2}a_l(E)P_l(\cos\theta)$$

G4NeutronHPInelastic

- Currently supported final states are (nA) n γ s (discrete and continuum), np, nd, nt, n ^{3}He, n α , nd2 α , nt2 α , n2p, n2 α , np , n3 α , 2n α , 2np, 2nd, 2n α , 2n2 α , nX, 3n, 3np, 3n α , 4n, p, pd, p α , 2p d, d α , d2 α , dt, t, t2 α , ^{3}He, α , 2 α , and 3 α .
- Secondary distribution probabilities are supported
  - isotropic emission
  - discrete two-body kinematics
  - N-body phase-space distribution
  - continuum energy-angle distributions
    - legendre polynomials and tabulation distribution
    - Kalbach-Mann systematic $A + a \rightarrow C \rightarrow B + b$, C:compound nucleus
  - continuum angle-energy distributions in the laboratory system

G4NeutronHPCapture

- The final state of radiative capture is described by either photon multiplicities, or photon production cross-sections, and the discrete and continuous contributions to the photon energy spectra, along with the angular distributions of the emitted photons.
- For discrete photon emissions
  - the multiplicities or the cross-sections are given from data libraries
- For continuum contribution
  - E neutron kinetic energy, E_γ photon energies

$$f\left(E \rightarrow E_\gamma\right) = \sum_i p_i(E) g_i\left(E \rightarrow E_\gamma\right)$$

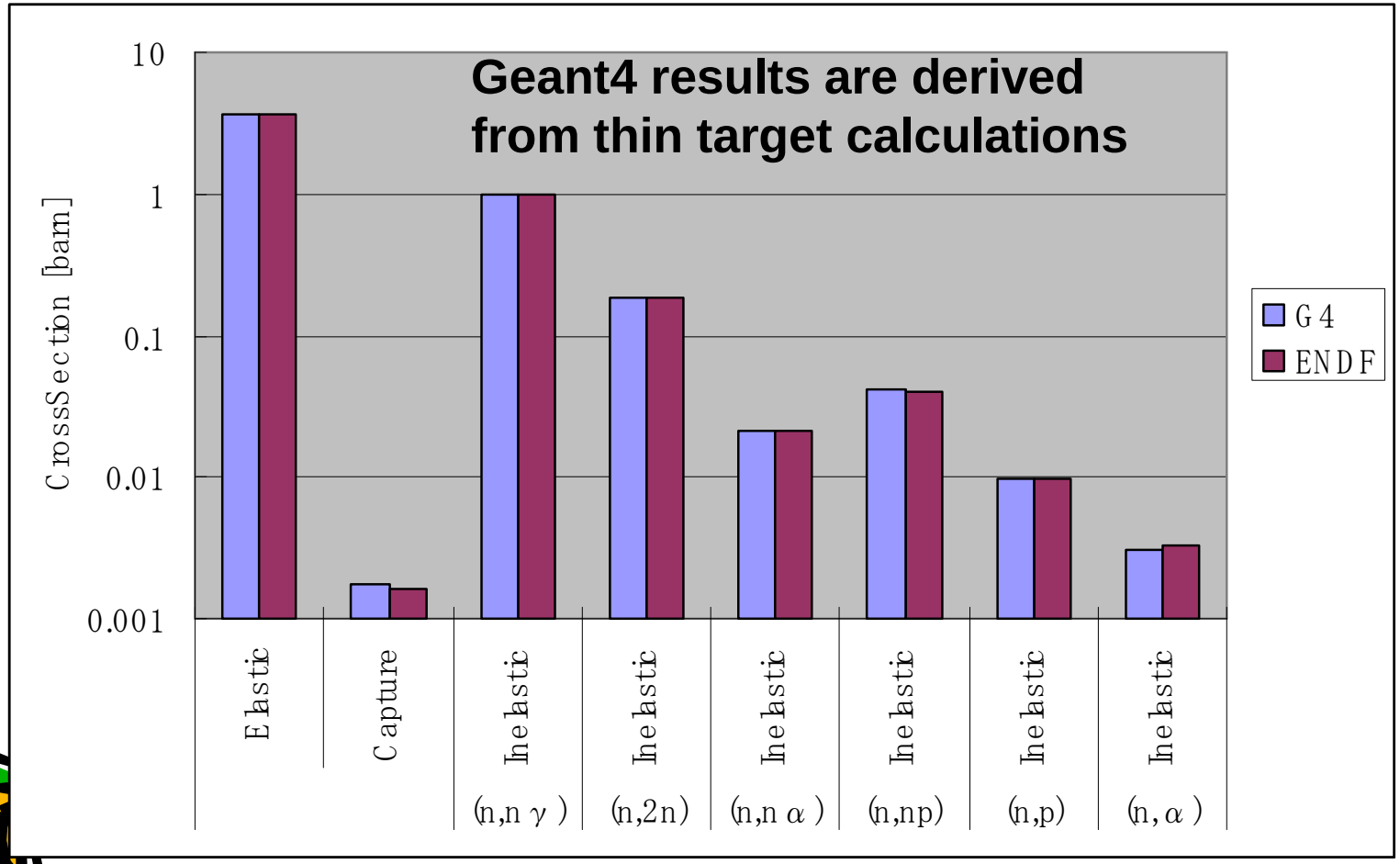
  - p_i and g_i are given from data libraries

G4NeutronHPFission

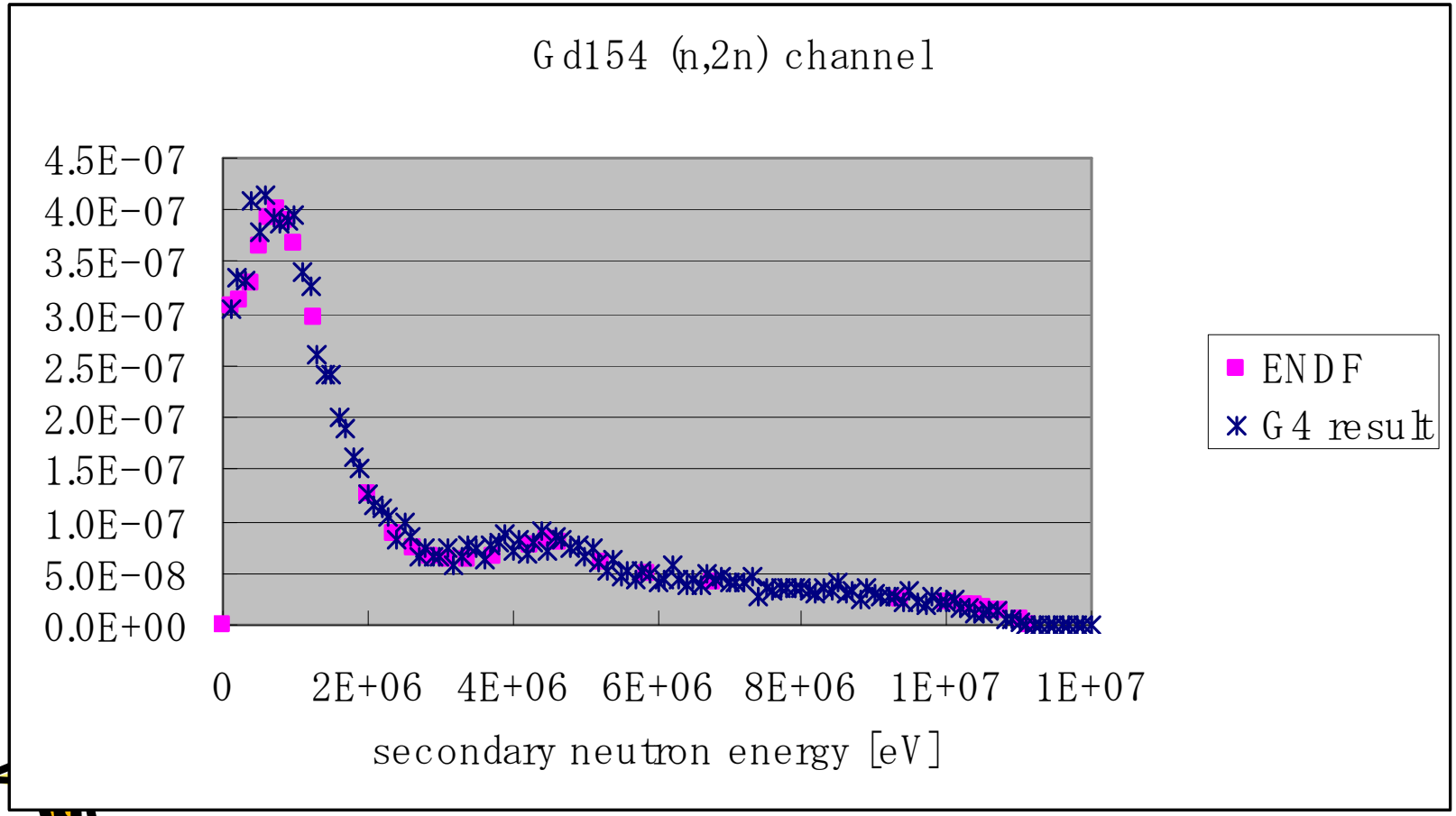
- Currently only Uranium data are available in G4NDL
- first chance, second chance, third chance and forth chance fission are into accounted.
- The neutron energy distributions are implemented in six different possibilities.
  - tabulated as a normalized function of the incoming and outgoing neutron energy - $f(E \to E')$
  - Maxwell spectrum - $f(E \to E') \propto \sqrt{E'} e^{E'/\Theta(E)}$
  - a general evaporation spectrum - $f(E \to E') \propto E' e^{E'/\Theta(E)}$
  - evaporation spectrum - $f(E \to E') = f\left(E'/\Theta(E) \right)$
  - the energy dependent Watt spectrum - $f(E \to E') \propto e^{E'/a(E)} \sinh \sqrt{b(E)E'}$
  - the Madland Nix spectrum - $f(E \to E') = \frac{1}{2}\left[g(E', \langle K_l \rangle) + g(E', \langle K_h \rangle) \right]$

Verification of HP Neutron models Channel Cross Sections

20MeV neutron on ^{157}Gd



Verification of HP Neutron models
Energy Spectrum of Secondaries



G4NeutornHPorLEModels

- Many elements remained without data for High Precision models.
- Those models make up for such data deficit.
- If the High Precision data are not available for a reaction, then Low Energy Parameterization Models will handle the reaction.
- Those can be used for not only for models (final state generator) but also for cross sections.
- Elastic, Inelastic, Capture and Fission models are prepared.

Thermal neutron scattering from chemically bound atoms

- At thermal neutron energies, atomic translational motion as well as vibration and rotation of the chemically bound atoms affect the neutron scattering cross section and the energy and angular distribution of secondary neutrons.
- The energy loss or gain of incident neutrons can be different from interactions with nuclei in unbound atoms.
- Only individual Maxwellian motion of the target nucleus (Free Gas Model) was taken into account the default NeutronHP models.

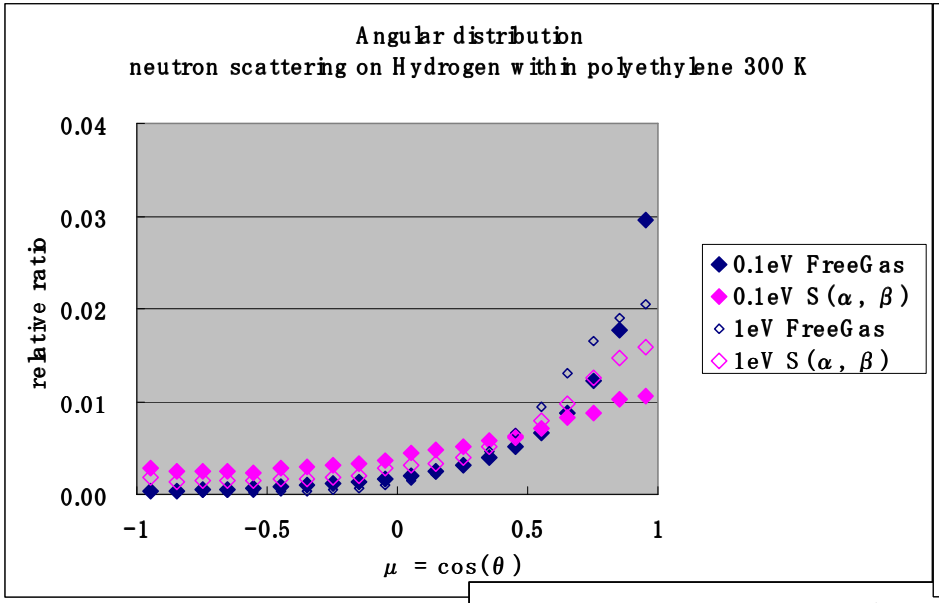
Thermal neutron scattering files from the evaluated nuclear data files ENDF/B-VI, Release2

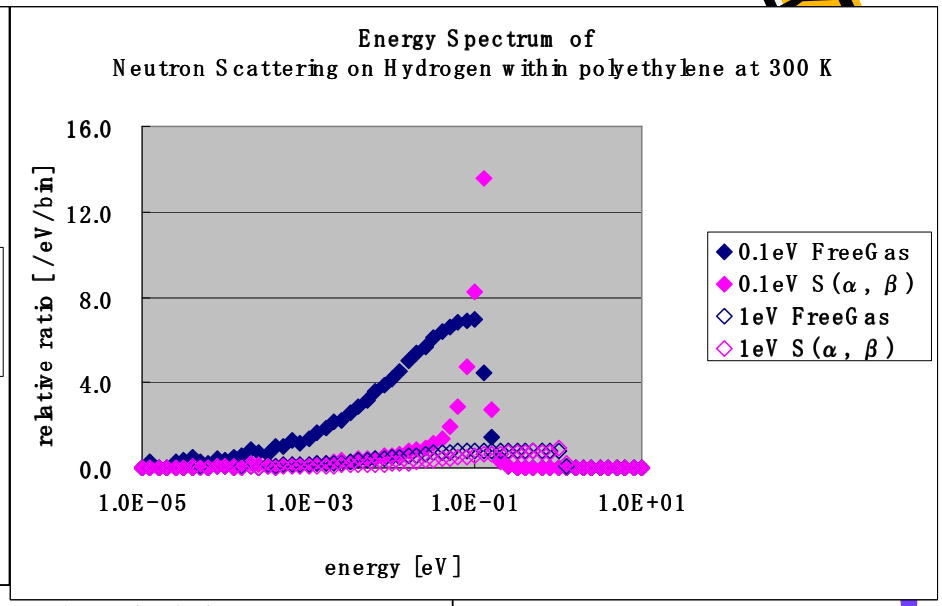
- These files constitute a thermal sub-library
- Use the File 7 format of ENDF/B-VI
- Divides the thermal scattering into different parts:
  - Coherent and incoherent elastic; no energy change
  - Inelastic; loss or gain in the outgoing neutron energy
- The files and NJOY are required to prepare the scattering law S(α , β) and related quantities.

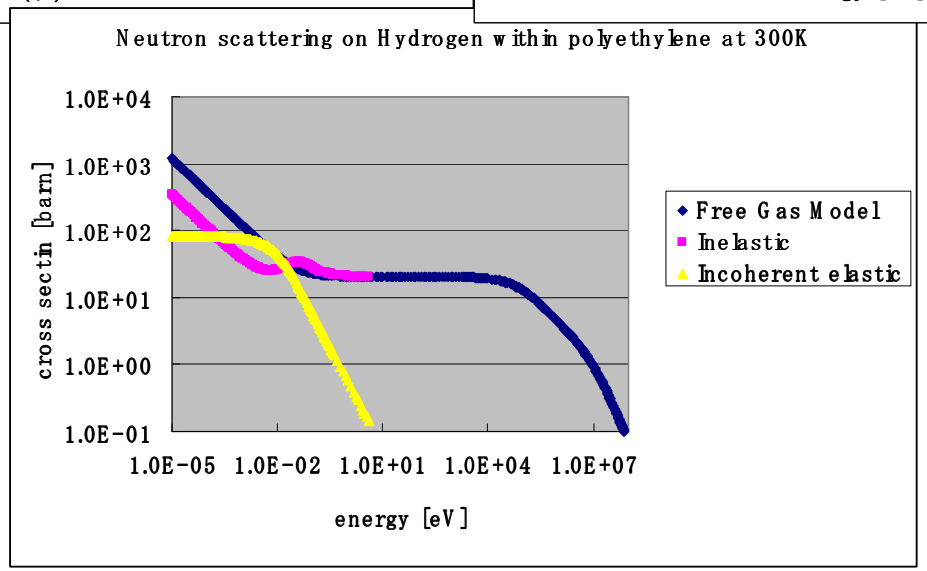
$$\text{Scattering cross section}: \sigma(E \to E', \mu) = \frac{\sigma_b}{2kT}\sqrt{\frac{E'}{E}}S(\alpha, \beta);$$

$$\text{momentum transfer}: \alpha = \frac{E' + E - 2\sqrt{E'E}\mu}{AkT}, \text{energy transfer}: \beta = \frac{E' - E}{kT}$$

Cross section and Secondary Neutron Distributions using S(α , β) model

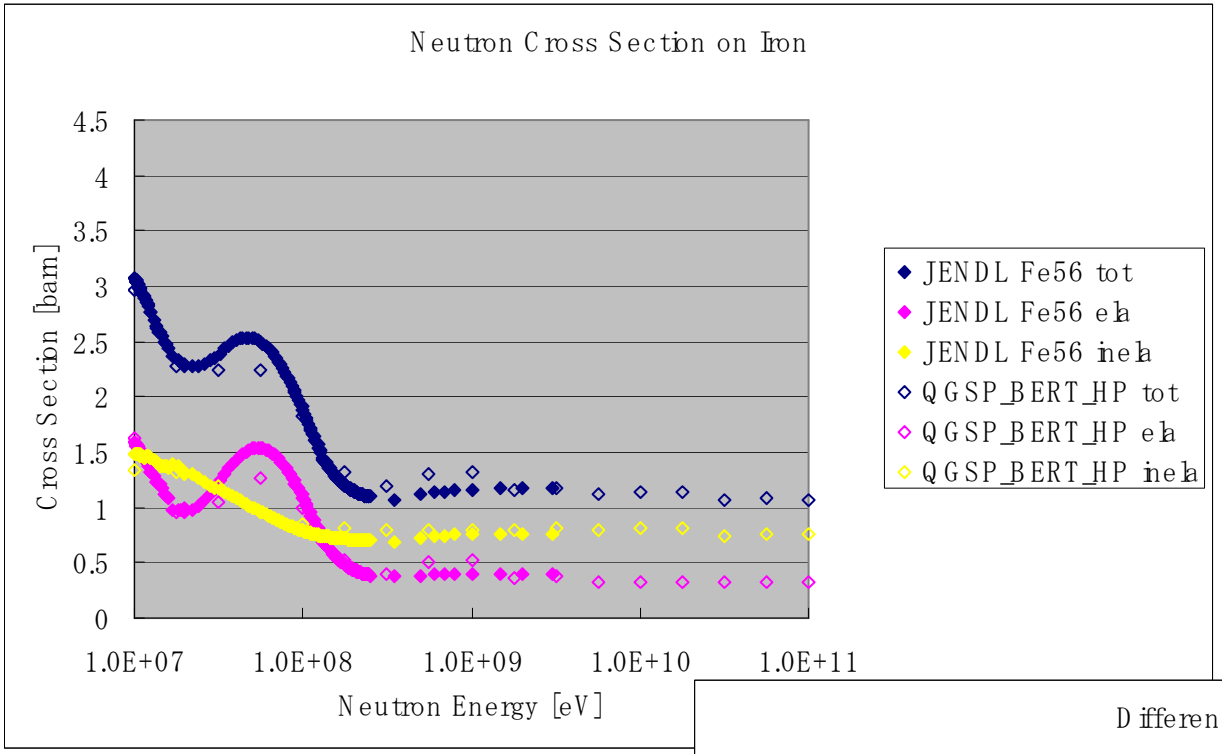






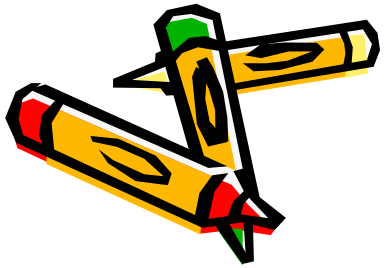
Japanese Evaluated Nuclear Data Library (JENDL) High Energy Files 2004

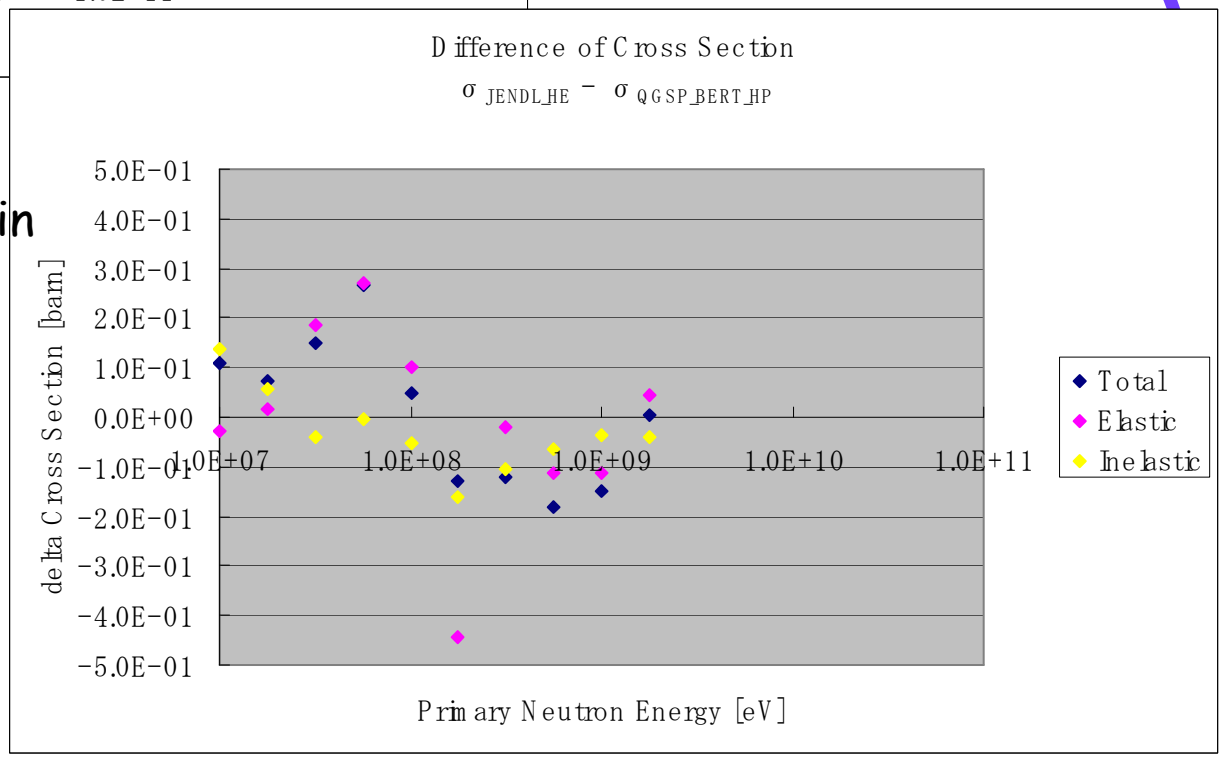
- JENDL Are been making by the Nuclear Data Evaluation Center of Japan Atomic Energy Agency with the aid of Japanese Nuclear Data Committee
- High Energy Files 2004
  - Neutron- and proton-induced reaction data up to 3 GeV for 66 nuclides.



Comparison JEND HE files to Cross Sections which used in QGSP_BERT_HP physics lists

Comparison carried out at Geant4 v8.0.p01





Physics List for NeutronHP

```
//For example  Elastic scattering below 20 MeV
G4HadronElasticProcess*    theNeutronElasticProcess   = new
    G4HadronElasticProcess();
// Cross Section Data set
G4NeutronHPElasticData* theHPElasticData = new
    G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theHPElasticData );
// Model
G4NeutronHPElastic* theNeutronElasticModel = new
    G4NeutronHPElastic();
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel)

G4ProcessManager* pmanager = G4Neutron::Neutron()->
    GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

Physics List for NeutronHPorLE

```
//For example  Elastic scattering below 20 MeV
G4HadronElasticProcess*    theNeutronElasticProcess   = new
    G4HadronElasticProcess();
// Model
G4NeutronHPorLElasticModel* theNeutronElasticModel = new
    G4NeutronHPorLElasticModel();
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel)
// Cross Section Data set
theNeutronElasticProcess->AddDataSet( theNeutronElasticModel-
    >GiveHPXSectionDataSet() );

G4ProcessManager* pmanager = G4Neutron::Neutron()->
    GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

Physics List for NeutronHPThermalScattering

```
G4HadronElasticProcess*    theNeutronElasticProcess   = new
    G4HadronElasticProcess();
// Cross Section Data set
G4NeutronHPElasticData* theHPElasticData = new G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theHPElasticData );
G4NeutronHPThermalScatteringData* theHPThermalScatteringData = new
    G4NeutronHPThermalScatteringData();
theNeutronElasticProcess->AddDataSet( theHPThermalScatteringData );
// Models
G4NeutronHPElastic* theNeutronElasticModel = new G4NeutronHPElastic();
theNeutronElasticModel->SetMinEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel);
G4NeutronHPThermalScattering* theNeutronThermalElasticModel = new
    G4NeutronHPThermalScattering();
theNeutronThermalElasticModel->SetMaxEnergy ( 4.0*eV );
theNeutronElasticProcess->RegisterMe(theNeutronThermalElasticModel);

// Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4Neutron::Neutron()-> GetProcessManager();
pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

Material Definitions for NeutronHPThermalScattering

```
// Create Element for Thermal Scattering
G4Element* elTSHW = new G4Element( "TS_H_of_Water" , "H_WATER" , 1.0 ,
    1.0079*g/mole );

G4Element* elTSH = new G4Element( "TS_H_of_Polyethylene" ,
    "H_POLYETHYLENE" , 1.0 , 1.0079*g/mole );

// Create Materials from the elements
G4Material* matH2O_TS = new G4Material( "Water_TS" , density =
    1.0*g/cm3 , ncomponents = 2 );
        matH2O_TS -> AddElement(elTSHW,natoms=2);
        matH2O_TS -> AddElement(elO,natoms=1);

G4Material* matCH2_TS = new G4Material( "Polyethylene_TS" , density =
    0.94*g/cm3 , ncomponents = 2 );
        matCH2_TS -> AddElement(elTSH,natoms=2);
        matCH2_TS -> AddElement(elC,natoms=1);
```

Physics List for JENDL High energy cross sections

```
//For example  Elastic scattering below 3 GeV
G4HadronElasticProcess*    theNeutronElasticProcess   = new
    G4HadronElasticProcess();
// Cross Section Data set  ( HP < 20MeV < JENDL HE)
G4NeutronHPElasticData* theHPElasticData = new
    G4NeutronHPElasticData();
theNeutronElasticProcess->AddDataSet( theNeutronElasticModel-
    >GiveHPXSectionDataSet() );
theNeutronElasticProcess->AddDataSet( theHPElasticData );
G4NeutronHPJENDLHEData*  theJENDLHEElasticData = new
    G4NeutronHPJENDLHEData();
theNeutronElasticProcess->AddDataSet(theJENDLHEElasticData);

    G4ProcessManager* pmanager = G4Neutron::Neutron()->
        GetProcessManager();
    pmanager->AddDiscreteProcess( theNeutronElasticProcess );
```

Ion Physics
Inelastic Reactions

- Cross Sections
- Model
  - G4BinaryLightIon
  - G4WilsonAbrasion

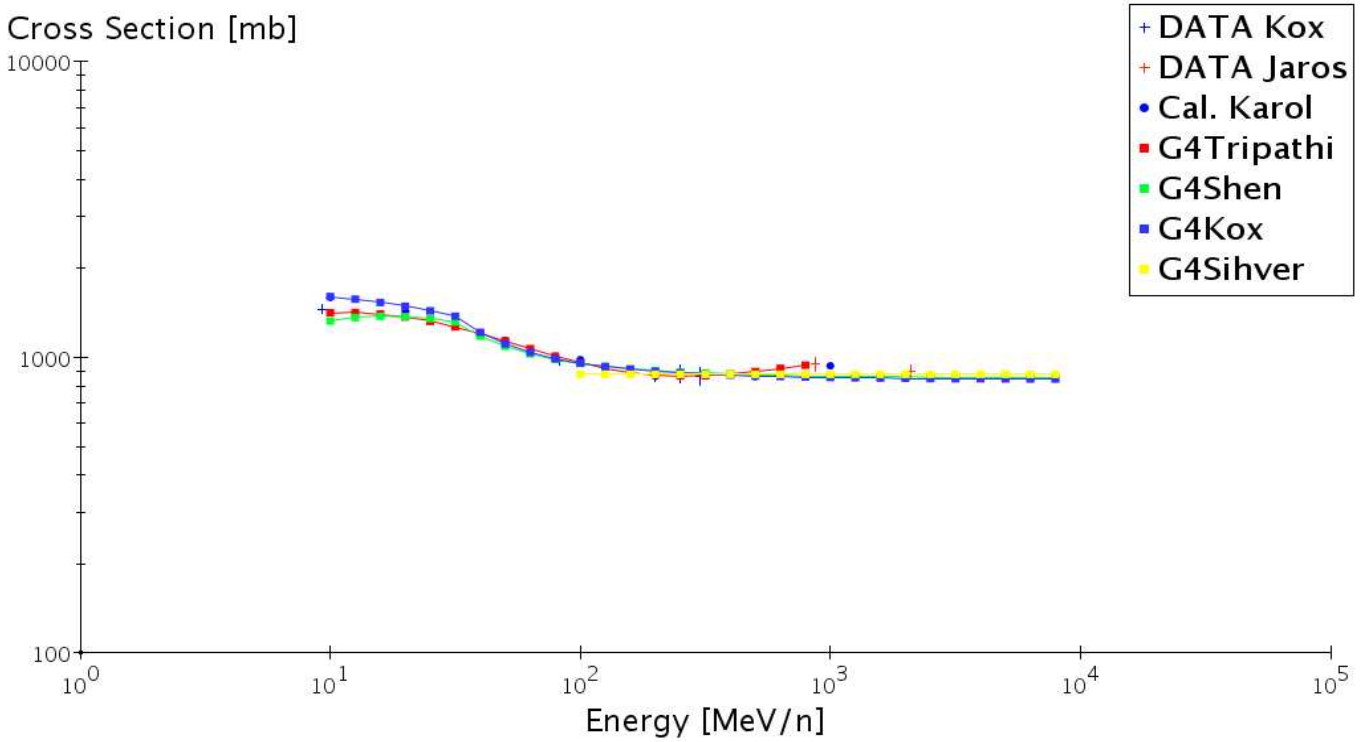
Cross Sections

- Many cross section formulae for NN collisions are included in Geant4
  - Tripathi, Shen, Kox and Sihver
- These are empirical and parameterized formulae with theoretical insights.
- G4GeneralSpaceNNCrossSection was prepared to assist users in selecting the appropriate cross section formula.

References to NN Cross Section Formulae implemented in Geant4

- Tripathi Formula
  - NASA Technical Paper TP-3621 (1997)
- Tripathi Light System
  - NASA Technical Paper TP-209726 (1999)
- Kox Formula
  - Phys. Rev. C 35 1678 (1987)
- Shen Formula
  - Nuclear Physics. A 49 1130 (1989)
- Sihver Formula
  - Phys. Rev. C 47 1225 (1993)

Inelastic Cross Section C12 on C12



Binary Cascade
~Model Principals~

- In Binary Cascade, each participating nucleon is seen as a Gaussian wave packet, (like QMD)

$$\phi(x, q_i, p_i, t) = \left(2/(L\pi) \right)^{3/4} \exp\left(-2/L(x - q_i(t))^2 + ip_i(t)x \right)$$

- Total wave function of the nucleus is assumed to be direct product of these. (no anti-symmetrization)
- This wave form have same structure as the classical Hamilton equations and can be solved numerically.
- The Hamiltonian is calculated using simple time independent optical potential. (unlike QMD)

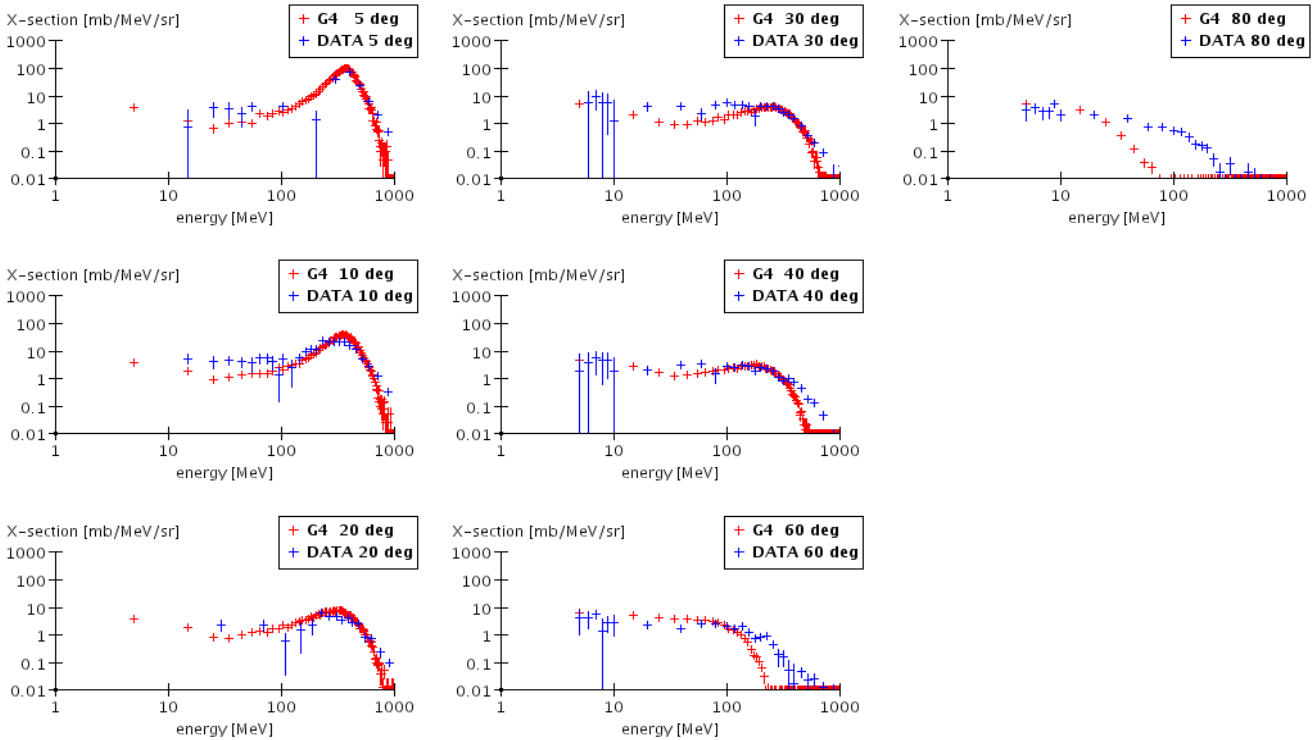
Binary Cascade ~nuclear model ~

- 3 dimensional model of the nucleus is constructed from A and Z.
- Nucleon distribution follows
  - A>16 Woods-Saxon model
  - Light nuclei harmonic-oscillator shell model
- Nucleon momenta are sampled from 0 to Fermi momentum and sum of these momenta is set to 0.
- time-invariant scalar optical potential is used.

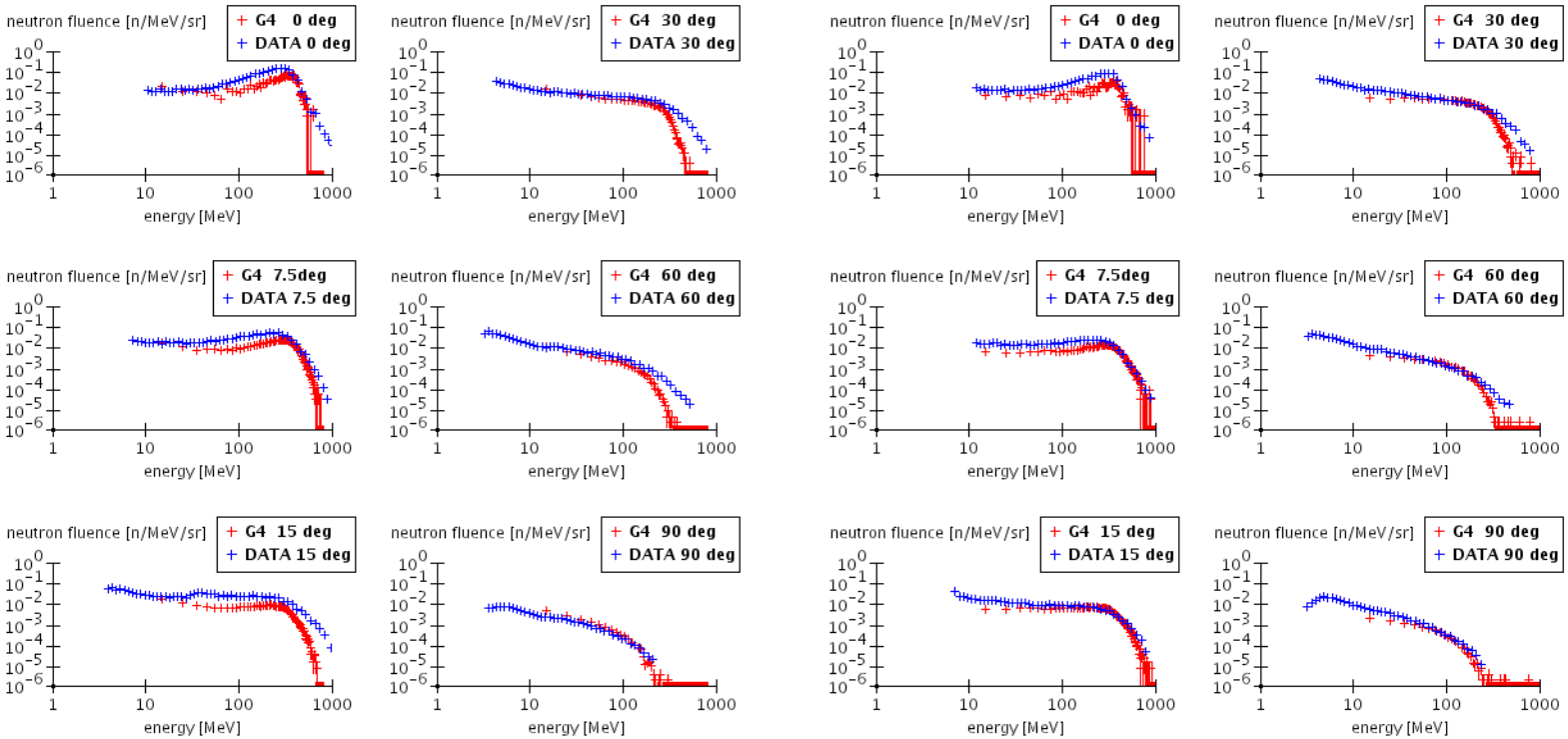
Binary Cascade
~ G4BinaryLightIonReaction ~

- Two nuclei are prepared according to this model (previous page).
- The lighter nucleus is selected to be projectile.
- Nucleons in the projectile are entered with position and momenta into the initial collision state.
- Until first collision of each nucleon, its Fermi motion is neglected in tracking.
- Fermi motion and the nuclear field are taken into account in collision probabilities and final states of the collisions.

Validation results
Neutrons from 400MeV/n Ne20 on Carbon



Neutron Yield
Fe 400 MeV/n beams

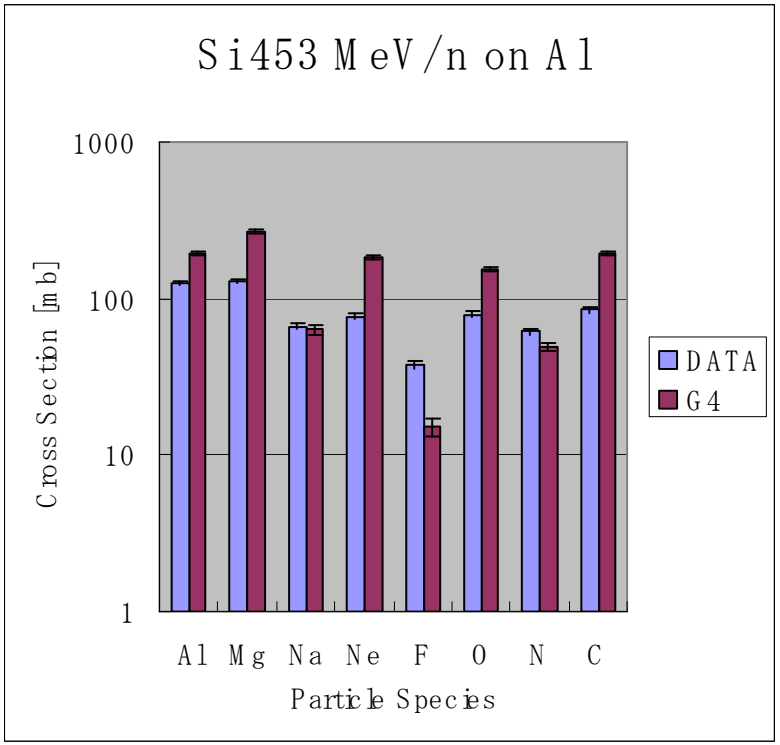


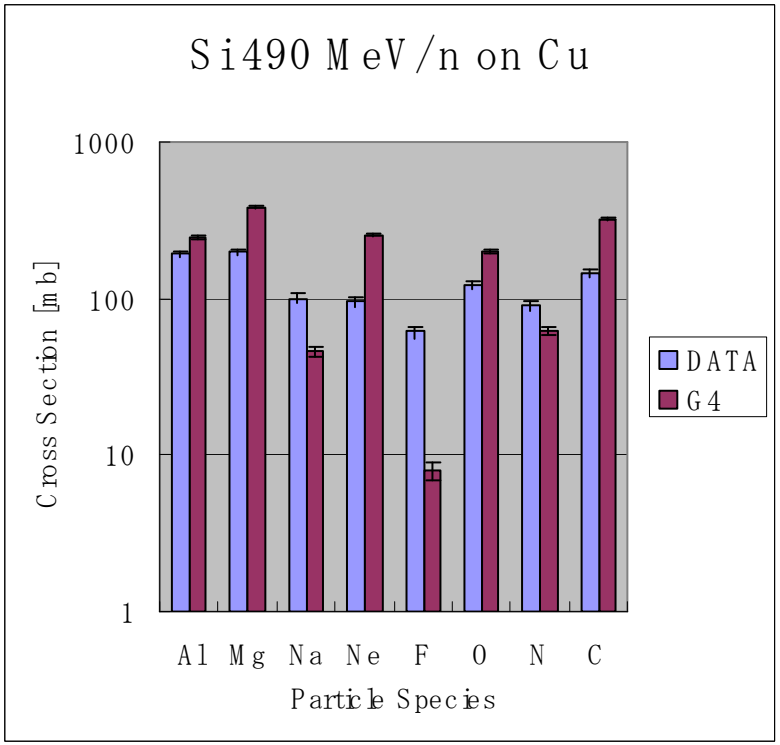
Copper Thick Target

Lead Thick Target

T. Kurosawa et al., *Phys. Rev.* **C62** pp. 04461501 (2000)

Fragment Production



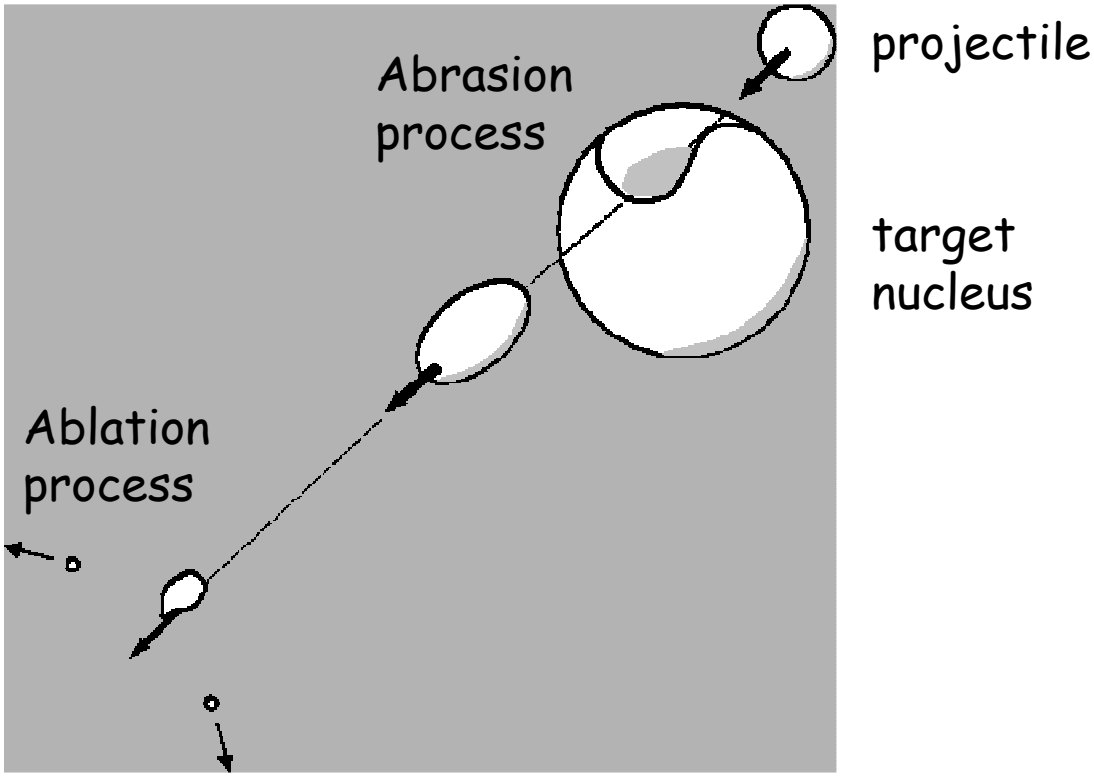


F. Flesch et al.,
J, RM, 34 237 2001

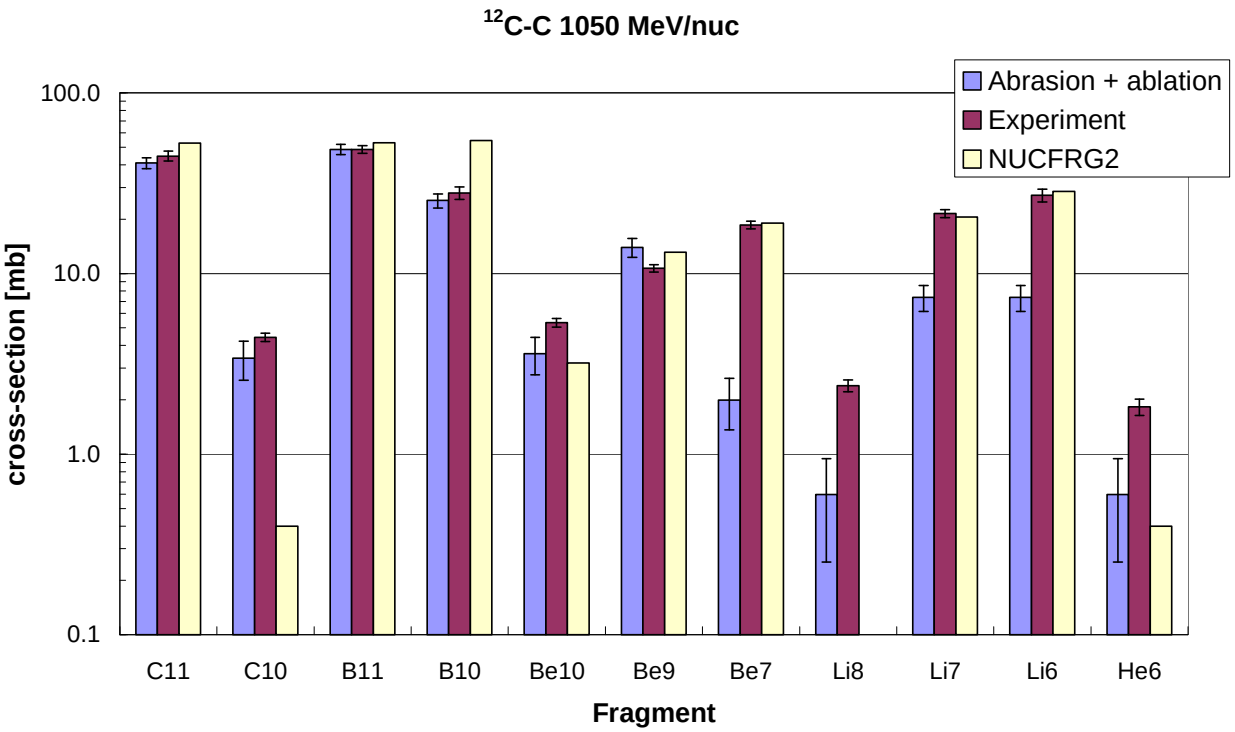
G4WilsonAbrasionModel & G4WilsonAblationModel

- G4WilsonAbrasionModel is a simplified macroscopic model for nuclear-nuclear interactions based largely on geometric arguments
- The speed of the simulation is found to be faster than models such as G4BinaryCascade, but at the cost of accuracy.
- A nuclear ablation has been developed to provide a better approximation for the final nuclear fragment from an abrasion interaction.
- Performing an ablation process to simulate the de-excitation of the nuclear pre-fragments, nuclear de-excitation models within Geant4 (default).
- G4WilsonAblationModel also prepared and uses the same approach for selecting the final-state nucleus as NUCFRG2 (NASA TP 3533)

Abrasion & Ablation



Validation of G4WilsonAbrasion model



Ion Physics
EelectorMagnetic Dissociation

- Electromagnetic dissociation is liberation of nucleons or nuclear fragments as a result of electromagnetic field by exchange of virtual photons, rather than the strong nuclear force
- It is important for relativistic nuclear-nuclear interaction, especially where the proton number of the nucleus is large
- G4EMDissociation model and cross section are an implementation of the NUCFRG2 (NASA TP 3533) physics and treats this electromagnetic dissociation (ED).

Validation of G4EMDissociaton Model

Target Emulsion nuclei: Ag 61.7%, Br 34.2%, CNO 4.0% and H 0.1%

Projectile	Energy [GeV/nuc]	Product from ED	G4EM Dissociation [mbarn]	Experiment [mbarn]
Mg-24	3.7	Na-23 + p	124 ± 2	154 ± 31
Si-28	3.7	Al-27 + p	107 ± 1	186 ± 56
	14.5	Al-27 + p	216 ± 2	165 ± 24† 128 ± 33‡
O-16	200	N-15 + p	331 ± 2	293 ± 39† 342 ± 22*

M A Jilany, *Nucl Phys*, **A705**, 477-493, 2002.

Physics List for Binary Light Ion

```
G4HadronInelasticProcess* theIPGenericIon = new
    G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() )
// Cross Section Data Set
G4TripathiCrossSection * TripathiCS= new G4TripathiCrossSection;
G4IonsShenCrossSection * ShenCS = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(ShenCS);
theIPGenericIon->AddDataSet(TripathiCS);
// Model
G4BinaryLightIonReaction * IonBC= new G4BinaryLightIonReaction;
theIPGenericIon->RegisterMe(IonBC);
//Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
    GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

..... And similar for d, t, He3, alpha Ions

Physics List for WilsonAbrasion

```
G4HadronInelasticProcess* theIPGenericIon =        new
    G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() );
// Cross Section Data Set
G4TripathiCrossSection * TripathiCS= new G4TripathiCrossSection;
G4IonsShenCrossSection * ShenCS = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(ShenCS);
theIPGenericIon->AddDataSet(TripathiCS);
// Model
G4BinaryLightIonReaction * theGenIonBC= new G4BinaryLightIonReaction;
theGenIonBC->SetMinEnergy(0*MeV);
theGenIonBC->SetMaxEnergy(0.07*GeV);
theIPGenericIon->RegisterMe(theGenIonBC);
G4WilsonAbrasionModel* theGenIonAbrasion = new G4WilsonAbrasionModel();
theIPGenericIon->RegisterMe(theGenIonAbrasion);
//Apply Processes to Process Manager of GenericIon
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()-> GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Physics List for EMDissociation

```
G4HadronInelasticProcess* theIPGenericIon =        new
    G4HadronInelasticProcess("IonInelastic",
    G4GenericIon::GenericIon() );
// Cross Section Data Set
G4EMDissociationCrossSection* theEMDCrossSection = new
    G4EMDissociationCrossSection;
theIPGenericIon->AddDataSet( theEMDCrossSection );
// Model
G4EMDissociation* theEMDModel = new G4EMDissociation;
theIPGenericIon->RegisterMe(theEMDModel);
//Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
    GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Ion Physics
Radio Active Decay

- To simulate the decay of radioactive nuclei
- Empirical and data-driven model
- α , β^+, β^- decay electron capture (EC) are implemented
- Data (RadioactiveDecay) derived from Evaluated Nuclear Structure Data File (ENSDF)
  - nuclear half-lives
  - nuclear level structure for the parent or daughter nuclide
  - decay branching ratios
  - the energy of the decay process.
- If the daughter of a nuclear decay is an excited isomer, its prompt nuclear de-excitation is treated using the G4PhotonEvaporation

Radio Active Decay

- Analog sampling is default
- Biasing sampling also implemented
  - The decays occur more frequently at certain times
  - For a given decay mode the branching ratios can be sampled with equal probability
  - split parent nuclide into a user-defined number of nuclides

Radio Active Decay

- Many users who are interested in Radio Active Decay also have interests "General Particle Source".
- This was introduced by Makoto briefly.
- **Geant4 General Particle Source Users Manual** (http://reat.space.qinetiq.com/gps/new_gps_sum_files/gps_sum.htm) is good place where users gets more detailed information.

Physics List for RadioactiveDecay

```
const G4IonTable *theIonTable =
G4ParticleTable::GetParticleTable()->GetIonTable();
G4RadioactiveDecay *theRadioactiveDecay = new G4RadioactiveDecay();

for (G4int i=0; i<theIonTable->Entries(); i++)
{
    G4String particleName = theIonTable->GetParticle(i)->GetParticleName();
    G4String particleType = theIonTable->GetParticle(i)->GetParticleType();

    if (particleName == "GenericIon")
    {
        G4ProcessManager* pmanager =
        theIonTable->GetParticle(i)->GetProcessManager();
        pmanager ->AddProcess(theRadioactiveDecay);
        pmanager ->SetProcessOrdering(theRadioactiveDecay, idxPostStep);
        pmanager ->SetProcessOrdering(theRadioactiveDecay, idxAtRest);
    }
}
```

Summary

- High Precision Neutron models are data driven models and its used evaluated data libraries.
- However the library is not complete because there are no data for several key elements.
- Geant4 has abundant processes for Ion interactions with matter and also without matter.
- Without any extra modules, users may simulate ion transportation in the complex and realistic geometries of Geant4.
- Validation has begun and the results show reasonable agreement with data. This work continues.