Hadronic Physics II

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Overview

Elastic process, cross section and model

Low Energy Neutron Physics

- High Precision Neutron Package
- Thermal Scattering S(α, β) model
- Low Energy Nuclear Data

Ion Physics

- Inelastic
  - Cross Section
  - Model
    - BIC
    - QMD
    - INCL++
- Electromagnetic Dissociation

Elastic Process

G4HadronElasticProcess

- “hadElastic” is the name of this process
- Having cross sections to calculate mean free path and models for final states.
- Use proton cut values for generation of recoil nucleus in all type of projectiles

Elastic cross sections

G4HadronElasticDataSet (GheishaElastic)

- Cross section from the Geant3/Gheisha routine GHESIG.

G4ChipsNeutron(Proton)ElasticXS (ChipsNeutron(Proton)ElasticXS)

- Cross section from extracted from CHIPS framework

G4ComponentAntiNuclNuclearXS (AntiAGlauber)

- elastic cross sections of anti-nucleons and light anti-nucleus interactions with nuclei using Glauber's approach.

G4BGGNucleonElasticXS: (Barashenkov-Glauber)

- Barashenkov-Glauber-Gribov cross section handles elastic scattering of protons and neutrons from nuclei using the Barashenkov parameterization below 91 GeV and the Glauber-Gribov parameterization above 91 GeV.

G4GGNuclNuclCrossSection (Glauber-Gribov nucleus nucleus)

- elastic cross sections for nucleus-nucleus collisions using the Glauber model with Gribov corrections

Elastic Models

G4HadronElastic (hElasticLHEP)

- from the Geant3/Gheisha

G4ChipsElasticModel (hElasticCHIPS)

- from CHIPS framework

G4ElasticHadrNucleusHE (hElasticGlauber)

- high energy hadron-nucleus elastic scattering for the kinetic energy T > 1 GeV

G4AntiNuclElastic (AntiAElastic)

- for AntiNuclear Nuclear Elastic Scattering

G4NuclNuclDiffuseElastic (NNDiffuseElastic)

- Final state production model for nucleus-nucleus elastic scattering

Low energy (< 20MeV) neutrons physics

High Precision neutron package

Thermal Scattering S(α,β) Model

Low Energy Nuclear Data package

G4NDL
(Geant4 Neutron Data Library)

The neutron data files for High Precision Neutron model

Point-wise cross section data

Most data are converted from ENDF/B-VII.r1 with processing NJOY-99.u364 for resonance reconstruction

- Tolerance of the processing is 0.001
- We are still using NJOY99, and once NJOY2010 becomes available we will re-processing

Following isotopes are exceptions.

- Several data files have trouble in NJOY processing or data file itself (MT600 block exists without MT103 block)
- For these isotopes, trying to use data files in ENDF/B-VII.r0 or VI.r8
- 4Be7, 33As74, 69Tm168, 69Tm169 and 74W180 (6 isotopes) are left no data

Total 417 isotopes data were converted.

- Data files for heavier than U are omitted from public release.

Data files are zlibed for reducing sizes.

The data format is similar ENDF-6 formats, however it is not equal to.

Evaluated Nuclear Data File (ENDF)

"ENDF" is used in two meanings

- One is a name of Data Formats and Procedures
  - How to write Nuclear Data files
  - How to use the Nuclear Data files
  - ENDF-6 is the latest version
    - Usually use numerical number to represent it version
- The other is a name of recommended libraries of USA nuclear data projects.
  - ENDF-VII.r1 is the latest
    - Usually use Roman numerals as the version number

NeutronHP package

Elastic, Inelastic, Capture and Fission models and cross sections

- Register them to Elastic, Inelastic Capture and Fission processes

Some important features of NeutronHP

Target thermal motions including Doppler broadening of the resonances are calculated on-the fly.

- Very CPU intense
- May be able to accelerate by GPU

Model does not guarantee energy and momentum conservation in multi body (>3) final states

- See later slide
- Not bug, but feature!

Description of ENDF data file is not complete in many reactions

- The worst case, only channel cross section is provided
- In such cases, neutronHP uses other Geant4 models in producing final states

Ultra cold neutrons (<<10^{-5} eV) may have trouble in transportation

- This is basically caused by the numerical precision of floating number of double (64bit)

Gravity is not included in default

- May become important in ultra cold neutron
- Implementation of add-on process for gravity is not difficult

models
Channel Cross Sections

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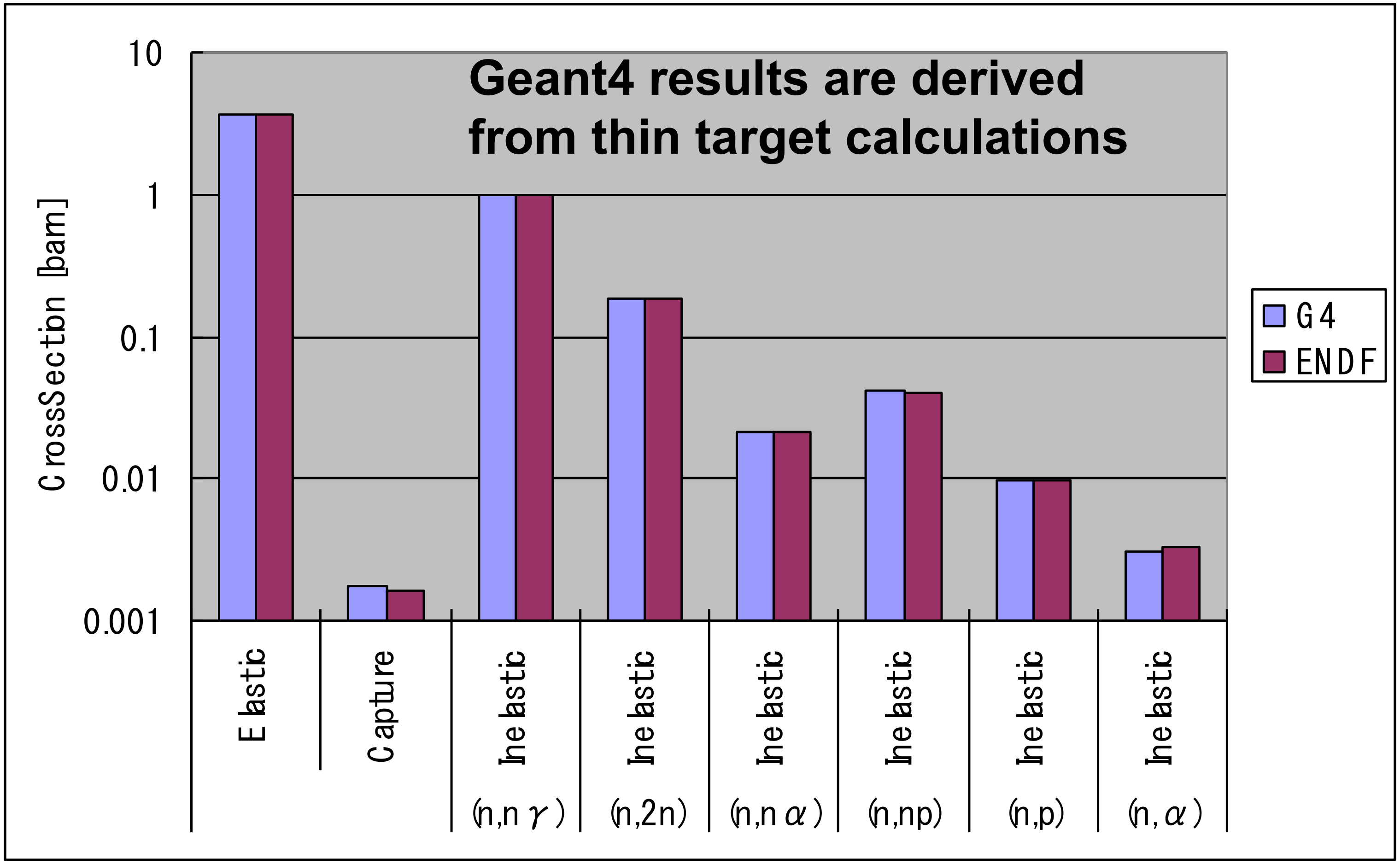
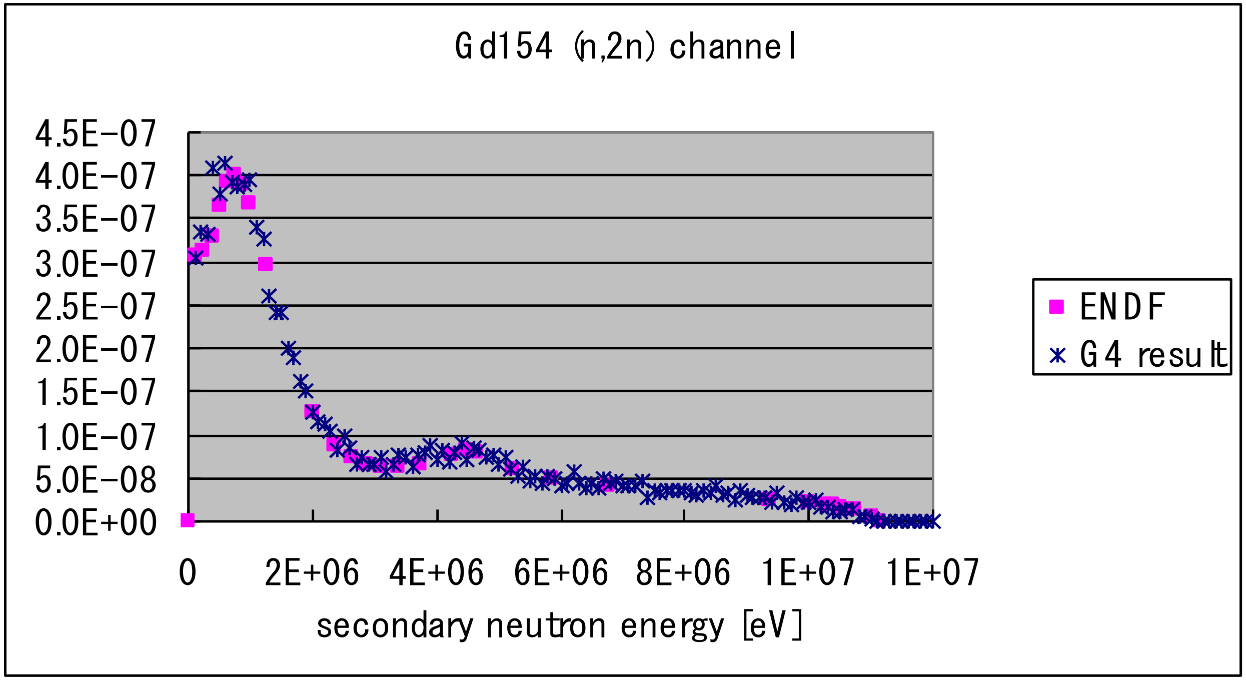
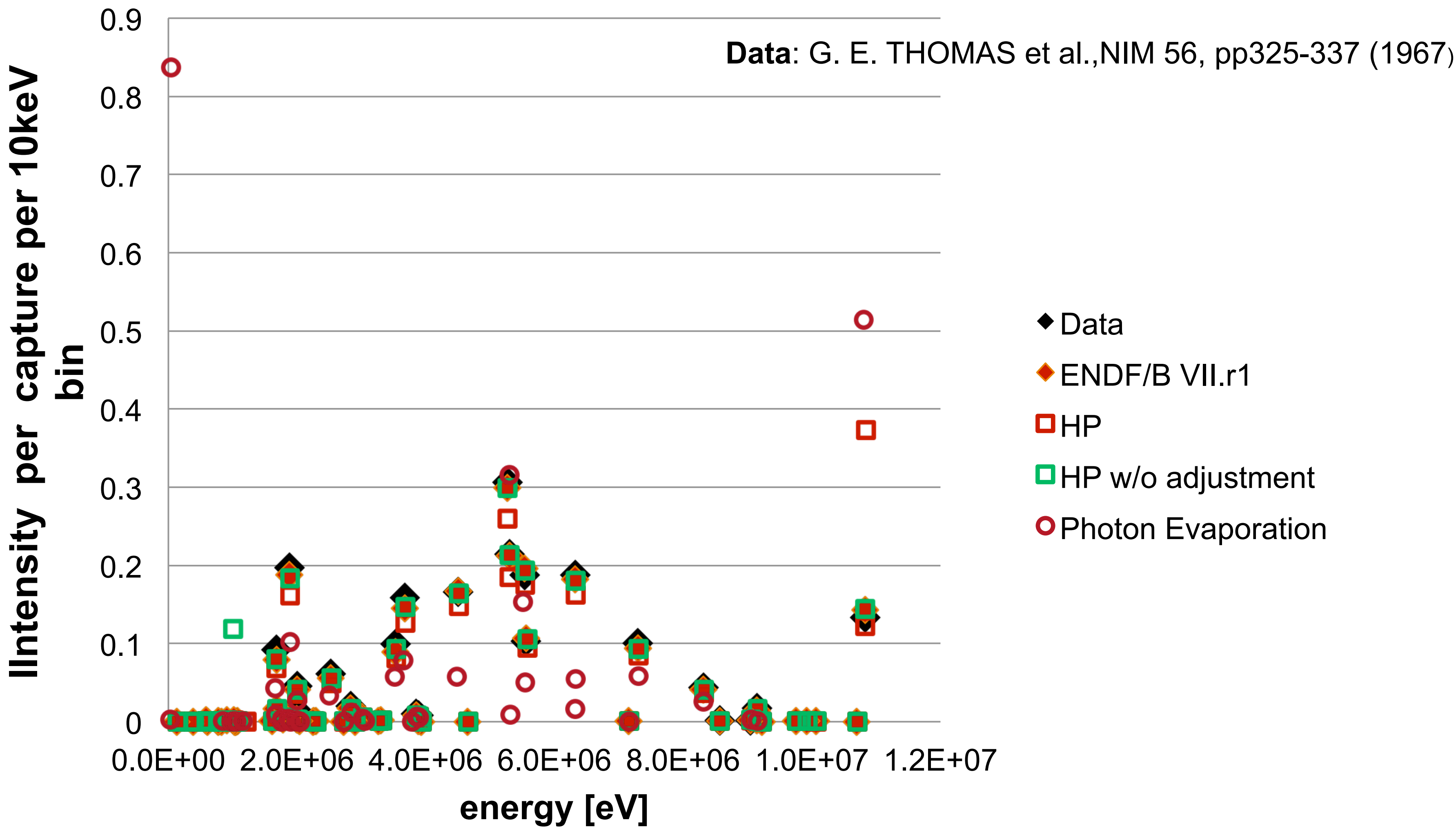
20MeV neutron on ^{157}Gd



Energy Spectrum of Secondary Particles



Validation of gammas emission from neutron captured by Nitrogen nucleus



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.

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

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

Material Definitions for NeutronHPThermalScattering

Thermal neutron scattering files from ENDF/B-VII thermal data (ENDF-6 File 7) are converted into G4NDL by NJOY99.u364 with reconstruction tolerance of 0.02

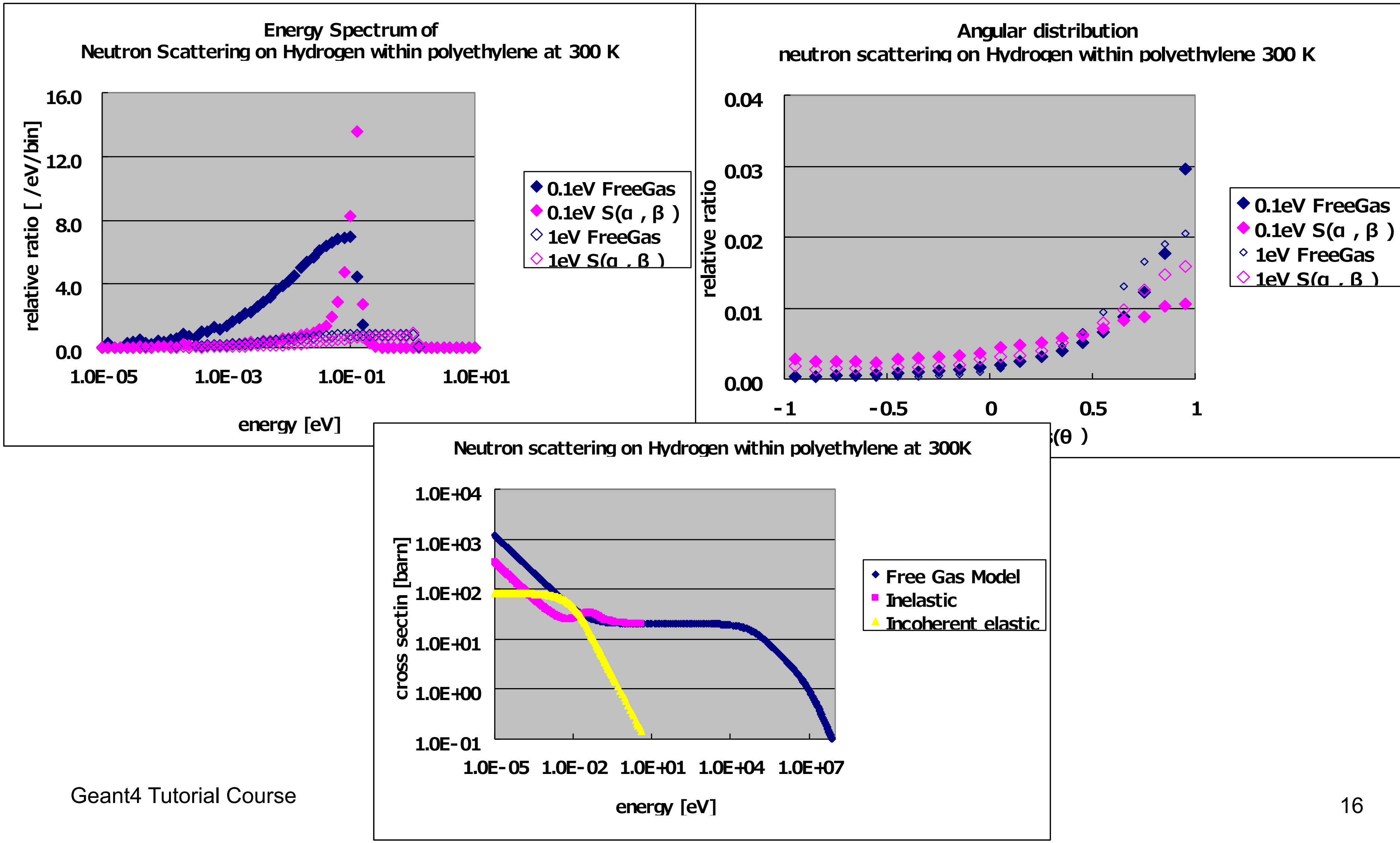
- There are about 20 materials in ENDF-VII thermal scattering

To activate NeutronHPThermalScattering, a volume must be made from elements having specific names like “TS_H_of_Water”.

You may also be able to use a material in pre defined material like G4_WATER.

- However not all support materials are in pre defined material database.

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



General Interaction Data Interface (GIDI) and Geant4 Low Energy Nuclear Data (G4LEND)

GIDI is a newly developed data format for nuclear data

- More modern design than current nuclear formats(ENDF) established in the 1960'

LEND is Geant4 interface for GIDI

Follows Hadronic Framework of Geant4, separated cross section and model as final state generator

Manage target nuclei data in GIDI

Pre-calculated data for certain temperatures are used.

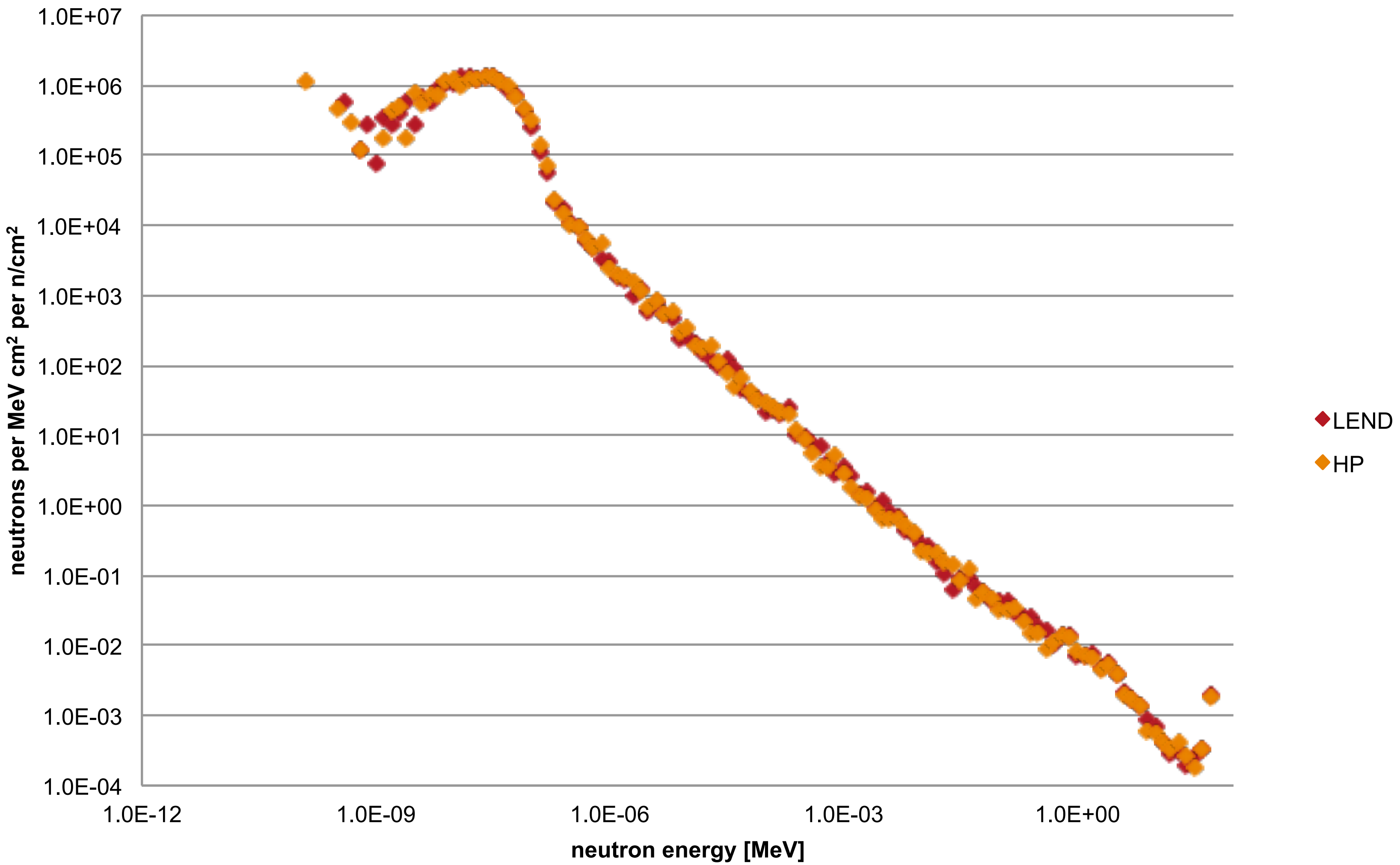
- 300, 1160 and 3590 K

Data file are separately distributed from Geant4

- ENDF VII.r0 is converted to GIDI compliant format and it is able to download from the web site operating at LLNL

An alternative to the low energy neutron package (NeutronHP) in Geant4

45-50MeV neutrons bombarding concrete slab
Neutron energy spectrum at depth of 1m



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 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 G4LEND

```
//For example  Elastic scattering below 20 MeV
G4HadronElasticProcess*    theNeutronElasticProcess   = new
G4HadronElasticProcess();
// Cross Section Data set
G4LENDElasticData* theHPElasticData = new
G4LENDData( G4Neutron::Neutron());
theNeutronElasticProcess->AddDataSet( theHPElasticData );
// Model
G4LENDElastic* theNeutronElasticModel = new G4LENDElastic();
theNeutronElasticProcess->RegisterMe(theNeutronElasticModel)

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

Ion Physics
Inelastic Reactions

Cross Sections

Model

- Binary Light Ion
- QMD
- INCL++

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)

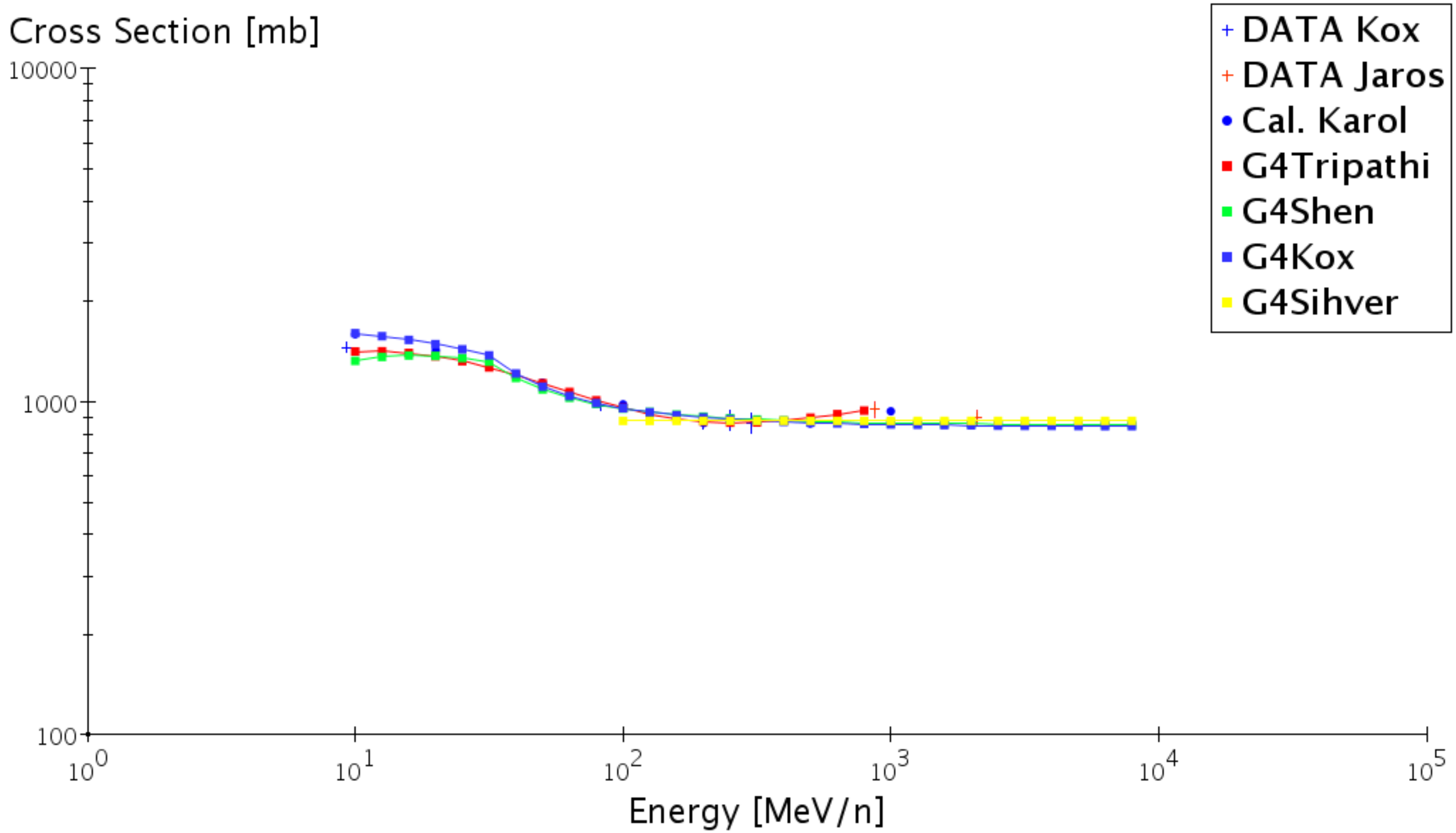
Shen Formula

- Nuclear Physics. A 49 1130 (1989)

Sihver Formula

- Phys. Rev. C 47 1225 (1993)

Inelastic Cross Section
C12 on C12



Glauber-Gribov nucleus nucleus

Calculates total and inelastic cross section, derives elastic as total – inelastic according to Glauber model with Gribov correction calculated in the dipole approximation on light cone.

Most reference physics lists recently switch to this cross section for nucleus-nucleus interactions

Binary Cascade
~Model Principals~

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

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

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).

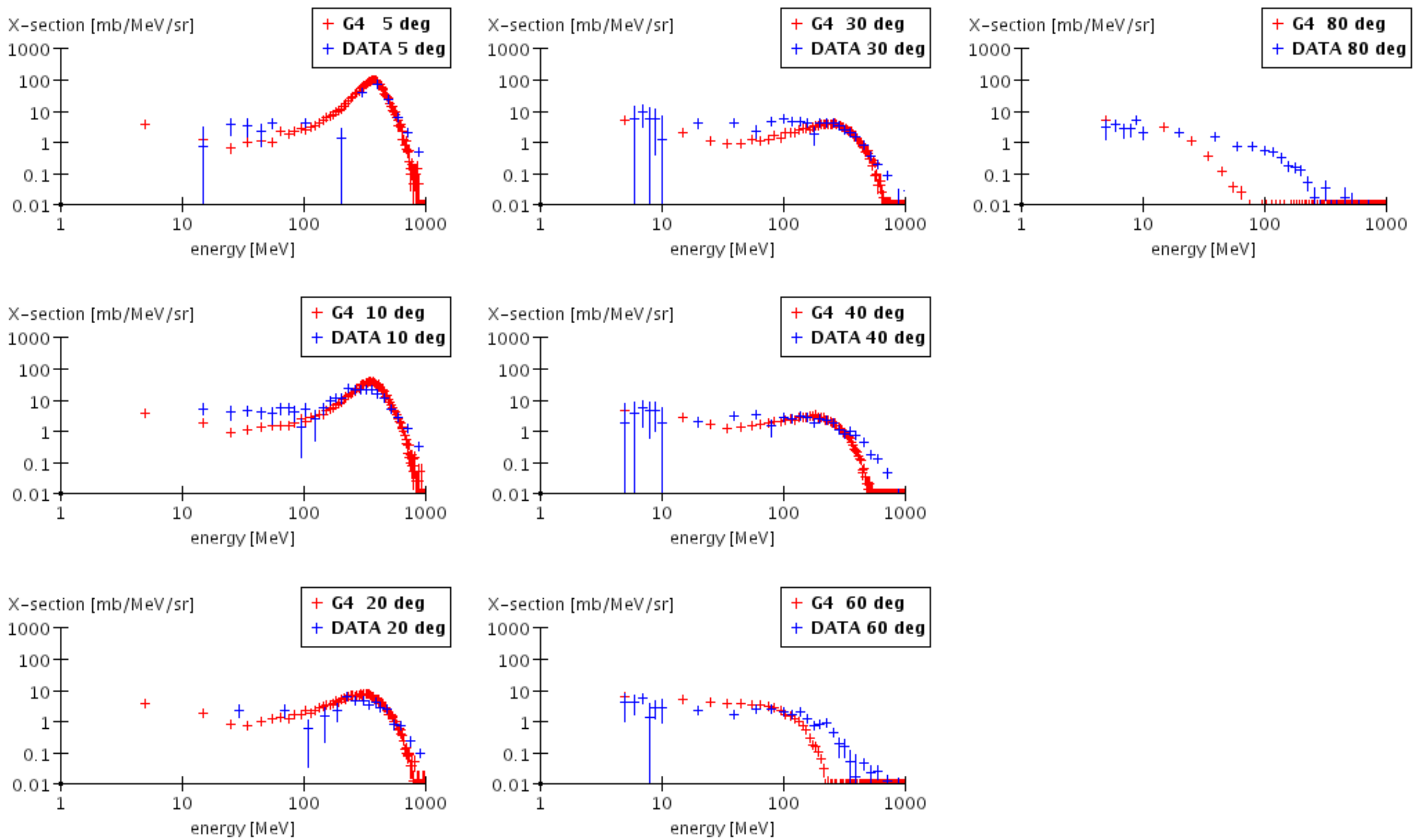
The lighter nucleus is selected to be projectile.

Nucleons in the projectile are entered with position and momenta into the initial collision state.

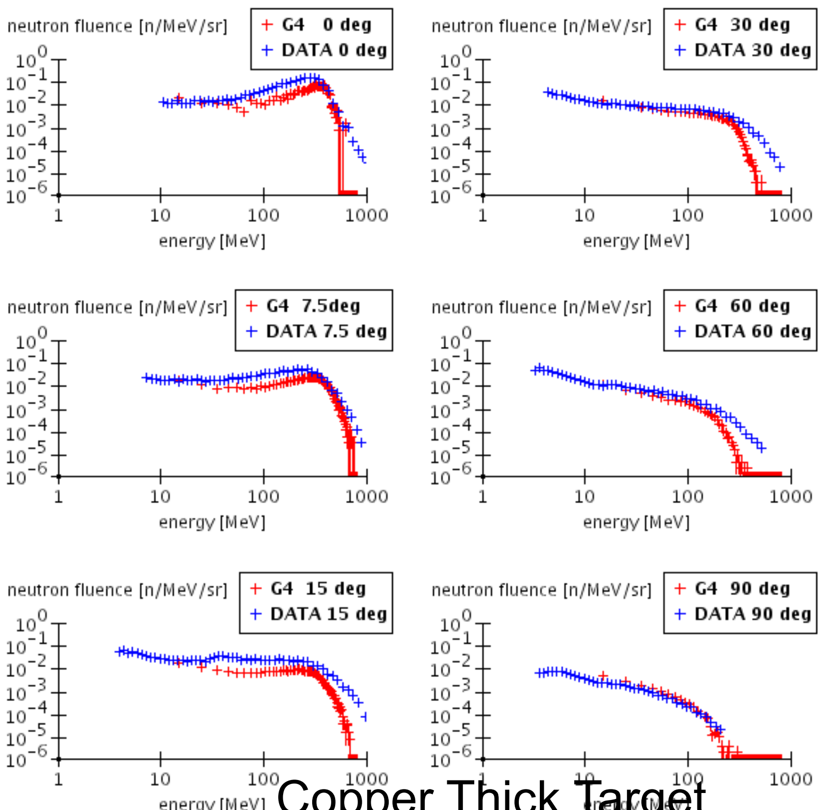
Until first collision of each nucleon, its Fermi motion is neglected in tracking.

Fermi motion and the nuclear field are taken into account in collision probabilities and final states of the collisions.

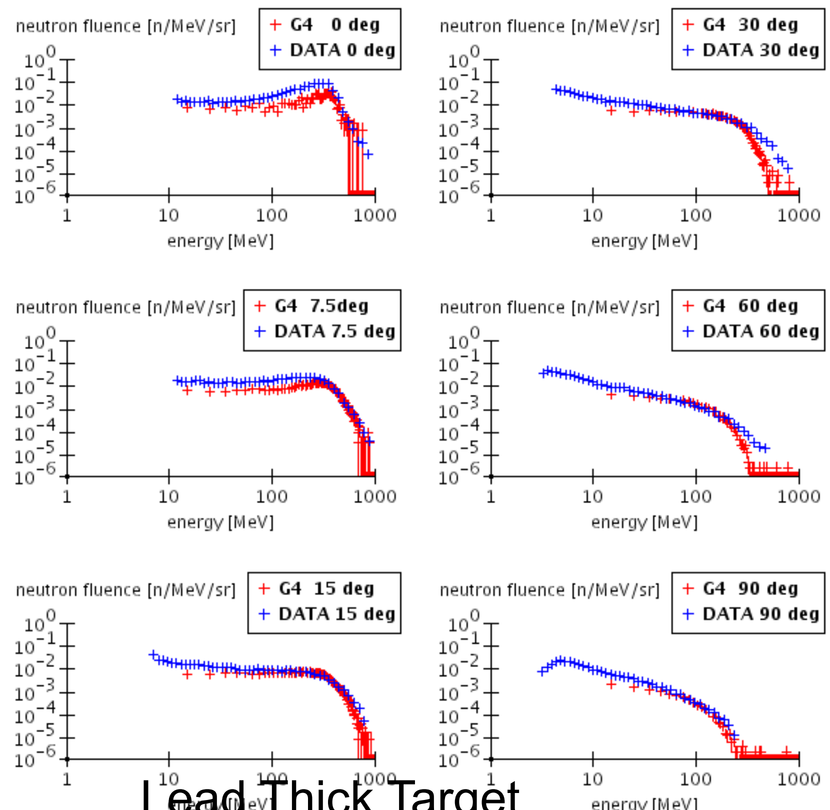
Validation results
Neutrons from 400MeV/n Ne20 on Carbon



Neutron Yield
Fe 400 MeV/n beams



Copper Thick Target



Lead Thick Target

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

G4QMD

Binary Light Ion Cascade is an Ion extension of Binary Cascade

However, in the model

- Neglects participant-participant scattering
- Uses simple time independent optical potential
- Does not provide ground state nucleus which can be used in molecular dynamics

The solution for overcoming these limitation and enabling the simulation of real HZE reactions is QMD (Quantum Molecular Dynamics)

QMD is quantum extension of classical molecular-dynamics model.

- Each nucleon is seen as a Gaussian wave packet
- Propagation with scattering term which takes into account Pauli principal

G4QMD

G4QMD create ground state nucleus based on JQMD, which can be used in MD

Potential field and field parameters of G4QMD is also based on JQMD with Lorentz scalar modifications

- "Development of Jaeri QMD Code" Niita et al, JAERI-Data/Code 99-042

Self generating potential field is used in G4QMD

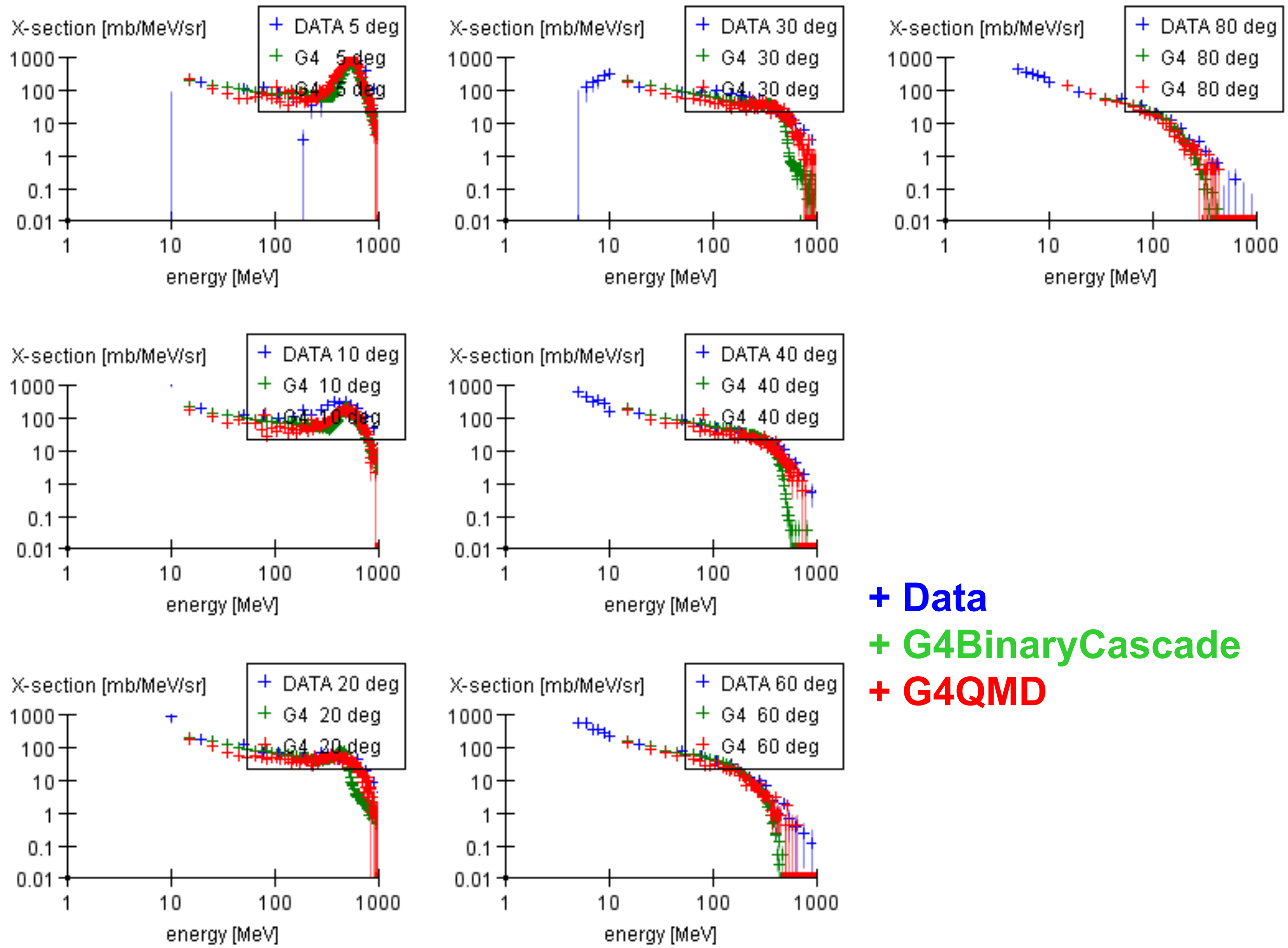
G4QMD uses scattering and decay library of Geant4

- Following 25 resonances are taken into account
- Δ from 1232 up to 1950
- N from 1400 up to 2250

G4QMD includes Participant-Participant Scattering

All major limitations of Binary cascade for Nucleus-Nucleus calculations are cleared in G4QMD

Ar40 560MeV/n on Lead
Secondary neutron spectra



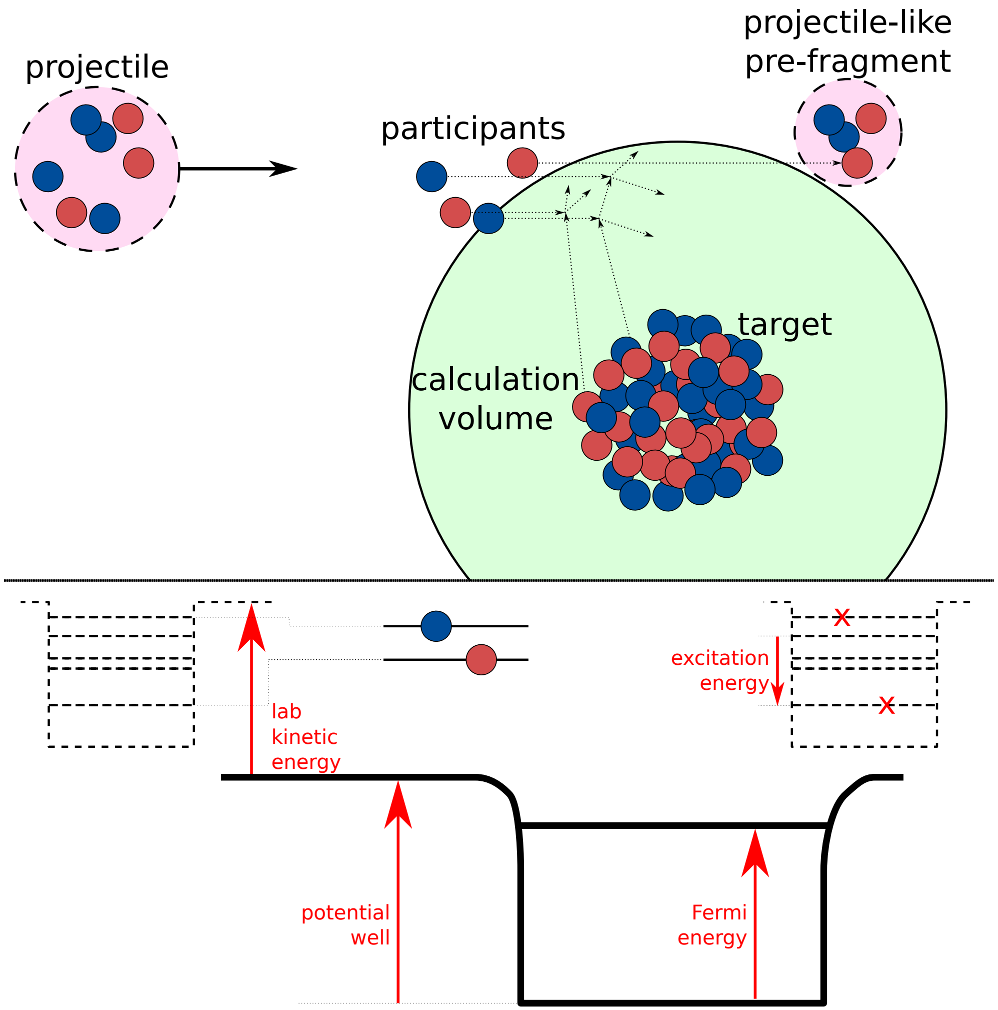
INCL++

Liège intranuclear-cascade model (INCL), jointly developed by CEA-Saclay (France) and the University of Liège (Belgium)

- Nucleon- and pion-induced reactions on nuclei between ~100 MeV and ~3 GeV
- Coupling to a suitable nuclear de-excitation model, it can reliably reproduce several observables such as emission spectra of particles and light ions, residual mass and charge distributions and residual recoil- velocity distributions
- Written in Fortran

INCL++ is a completely redesigned version of the INCL model in C++ for Geant4

Schematic depiction of the preparatory phase of a nucleus-nucleus reaction in INCL++



Double-differential cross section for neutron production from a 290 AMeV 12C+C reaction.

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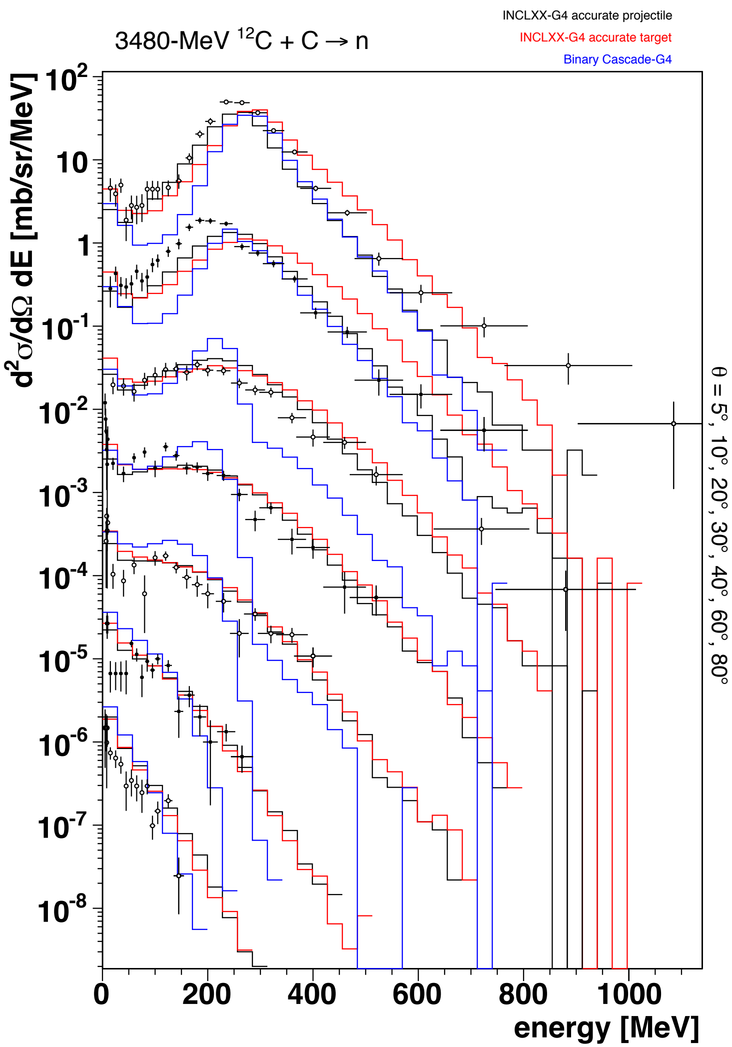

INCLXX-G4 projectile

INCLXX-G4 target

Binary Cascade

Y. Iwata et al., *Phys. Rev. C*, 64, 054609 (2001).

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 * TripathiCrossSection= new
G4TripathiCrossSection;
G4IonsShenCrossSection * aShen = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(aShen);
theIPGenericIon->AddDataSet(TripathiCrossSection);
// Model
G4BinaryLightIonReaction * theGenIonBC= new G4BinaryLightIonReaction;
theIPGenericIon->RegisterMe(theGenIonBC);
//Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Physics List for QMD

```
G4HadronInelasticProcess* theIPGenericIon =       new
G4HadronInelasticProcess("IonInelastic", G4GenericIon::GenericIon() );
// Cross Section Data Set
G4TripathiCrossSection * TripathiCrossSection= new
G4TripathiCrossSection;
G4IonsShenCrossSection * aShen = new G4IonsShenCrossSection;
theIPGenericIon->AddDataSet(aShen);
theIPGenericIon->AddDataSet(TripathiCrossSection);
// Model
G4QMDReaction * theGenIonQMD= new G4QMDReaction;
theIPGenericIon->RegisterMe(theGenIonQMD);
//Apply Processes to Process Manager of Neutron
G4ProcessManager* pmanager = G4GenericIon:: GenericIon()->
GetProcessManager();
pmanager->AddDiscreteProcess( theIPGenericIon );
```

Physics List for INCL++

Use reference physics lists of QGSP_INCLXX or FTFP_INCLXX

- INCL++ is used in ions reactions that one of the nucleus is equal to or lighter than carbon, otherwise Binary light ion cascade will handle the reactions.

You may use G4IonINCLXXPhysics constructor in your physics list.

For example RegisterPhysics(new G4IonINCLXXPhysics(ver));

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 );
```

Summary

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Many cross section and models are prepared for Elastic process. Refer reference physics lists, when you need to wright your own physics list.

High Precision Neutron models are data driven models and its used evaluated data libraries.

LEND package is designed for successor of High Precision Neutrons

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.