Implementing the Bertini Intra-Nuclear-Cascade in the Geant4 Hadronic Framework

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Outline

- Bertini intra-nuclear models
- Implementation in the Geant4 Hadronic Framework
- Physics validation
- Examples of functionality
- Latest model modifications and extensions

Introduction

Intra-nuclear cascade (INC) implementations such as HETC [1] have traditionally a wide range of applications in

- shielding,
- dose estimation,
- hadronic treatment planning,
- hadron calorimetry [2] and
- transmutation of nuclear waste materials.

[1] R. G. Alsmiller, Jr., F. S. Alsmiller and O. W. Hermann, "The High-energy Transport Code HETC88 and comparisons with experimental data," *Nucl. Instr. and Meth. A*, **295**, pp. 337-343 (1990).

[2] J. E. Brau, "Simulation of Hadronic Showers and ," *Nucl. Instr. and Meth. A*, **312**, pp. 483-514 (1992).

Introduction

Recently a renewed interest towards INC has been stimulated by

- Accelerator Driven Systems and
- spallation neutron sources.

Examples of this development are improvements in Liége INC model [1] and hadron-nucleus event generator validations made by EDDA Collaboration [2]

[1] A. Boudard et al., "Improvements of Intra-Nuclear Cascade Models Stimulated by Recent Spallation Data," *INPC 2001 AIP Conference Proceedings,* Berkeley, California (USA), 30 July – 3 August, Vol 610(1), pp. 300-304 (2002).

[2] K. Ackerstaff et al., "A Hadron-nucleus Collision Event Generator for Simulations at Intermediate Energies," *Nucl. Instr. and Meth. A*, **491**, pp. 492-506 (2002).

Introduction

Geant4 toolkit offers

- comprehensive range of tools for model developer,
- as well as tested functionality for simulating the passage of particles through matter.
- A general INC framework is provided.

Large number of various hadronic models are available[1],

- from fully parametric models, such as GHEISHA code[2],
- to highly theoretically driven models, such as CHIPS[3].

[1] N. Amelin, "Physics and Algorithms of the Hadronic Monte-Carlo Even Generators," *CERN/IT/99/6,* CERN (1999).

[2] H. Fesefeldt, "The Simulation of Hadronic Showers, Physics and Applications," *Report PITHA 85/02,* Aachen (1985).

[3] P. V. Degtyarenko, M. V. Kossov and H.-P. Wellisch, "Chiral Invariant Phase Space Event Generator," *The European Physical Journal A*, **9**, pp. 411-420 (2000).

Bertini Cascade Models

The intra-nuclear cascade model developed by Bertini solves on the average the Boltzmann equation.

We present here an implementation of this classic INC model.

In inelastic particle-nucleus collisions

- a fast phase (10^{-23} – 10^{-22} s) of INC results in a highly exited nucleus, and is followed
- by fission and
- pre-equilibrium emission;
- a slower (10^{-18} – 10^{-16} s) compound nucleus phase follows with
- evaporation.

Bertini Cascade Models

The Bertini nuclear model[1] consist of a

- three-region approximation to the continuously changing density distribution of nuclear matter.
- Relativistic kinematics is applied throughout the cascade and
- the cascade is stopped when all the particles, which can escape the nucleus, have done so.

Pauli exclusion principle

- is taken into account and
- conformity with the energy conservation law is checked.

[1] A. S. Iljinov, M. V. Kazarnovsky and E. Ya. Paryev, *Intermediate-energy Nuclear Physics,* CRC Press, Boca Raton, Florida (USA). (1994).

Bertini Cascade Models

- Path lengths of nucleons in the nucleus
  - are sampled according to the local density and
  - free nucleon-nucleon cross-sections.
- Angles after collisions are sampled from experimental differential cross-sections.
- Tabulated total reaction cross-sections are calculated by Letaw's formulation[1].

[1] S. Pearlstein, "Medium-energy Nuclear Data Libraries. A Case Study, Neutron and Proton -induced Reactions in ^{56}Fe," *The Astropysical Journal*, **346**, pp. 1049-1060 (1989).

Bertini Cascade Models

Models included[1] are

- Bertini INC model with exitons,
- pre-equilibrium model,
- nucleus explosion model,
- fission model, and
- evaporation model.

Intermediate energy nuclear reactions up to 10 GeV energy are treated for

- proton, neutron,
- pions, (kaons in preparation)
- photon, and nuclear isotopes.

[1] A. Heikkinen and N. Stepanov, "Bertini Intra-nuclear Cascade Implementation in Geant4," *Proceedings of CHEP03, nucl-th0306008*, La Jolla, California, 24–28 March, (2003).

Bertini Cascade Models

For pion the INC cross-sections are provided to treat elastic collisions and inelastic channels:

- $\pi^- n \rightarrow \pi^0 n$
- $\pi^0 p \rightarrow \pi^+ n$
- $\pi^0 n \rightarrow \pi^- p$.

Multiple particle production and following s-wave pion absorption channels are implemented:

- $\pi^+ nn \rightarrow pn$
- $\pi^+ pn \rightarrow pp$
- $\pi^0 nn \rightarrow X$
- $\pi^0 pn \rightarrow pn$
- $\pi^0 pp \rightarrow pp$
- $\pi^- nn \rightarrow X$
- $\pi^- pn \rightarrow nn$
- $\pi^- pp \rightarrow pn$.

Implementing Bertini Cascade

Geant4 hadronic shower framework[1] follow the Russian dolls approach to implement framework design.

- Hierarchy of frameworks encapsulate the common logic of a particular use-case.
- Hadronics Level 4 framework allows concrete implementation of INC.
- Implementers of concrete intra-nuclear transport code need to use *G4VIntraNuclearTransportModel*.

[1] J. P. Wellisch, “Hadronic Shower Models in Geant4 – the Frameworks”, *Comput. Phys. Commun.*, **140**, pp. 65-75 (2001).

Implementing Bertini Cascade

Following the coding guidelines provided by the hadronic framework,

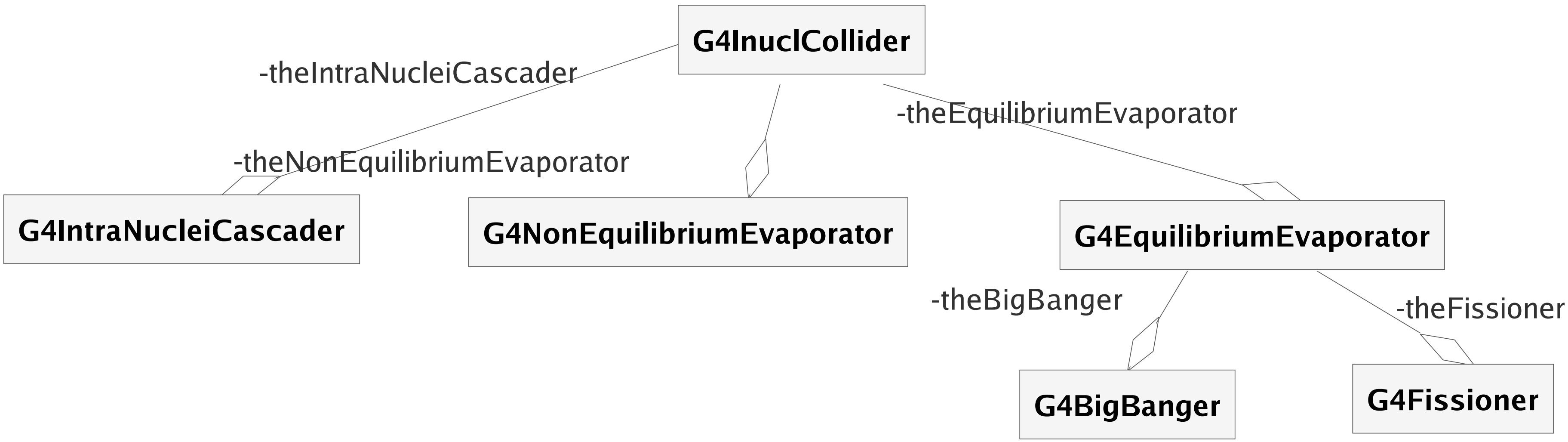
- Bertini cascade model interface class *G4CascadeInterface* inherits from *G4VIntraNuclearTransportModel* and
- implements hadronic final state generator with more than 35 classes.

Responsibilities of key classes in Geant4 Bertini cascade implementation.

Responsibility	Class name	Note
Interface	*G4CascadeInterface*	Implements INC framework.
Colliding particles	*G4ElementaryParticleCollider*	
Sub-model management	*G4InuclCollider*	
Nuclei model	*G4InuclNuclei*	
INC model	*G4IntraNucleiCascader*	Actual Bertini cascade treatmen
Exiton model	*G4NonEquilibriumEvaporator*	Integrated with INC model.
Explosion model	*G4BigBanger*	
Fission model	*G4Fissioner*	Uses *G4FissionConfiguration*.
Evaporation model	*G4EquilibriumEvaporator*	Full de-exitation of nuclei.

Implementing Bertini Cascade

Unified Modeling Language diagram demonstrating relationships between key classes in Geant4 Bertini cascade implementation.



Implementing Bertini Cascade

With the use of

- object oriented technology and
- layered framework design

we achieve a transparency of the physics.

Clear separation of the physics models allow

- critical analysis,
- development, and
- extendibility

of models behind various components of the particle emission.

The implementation provides some practical tools,

- such as classes *G4WatcherGun* and
- *G4Analyser*

for validating the physics results of INC models.

Implementing Bertini Cascade

Latest release is now found to be stable.

- (After some memory leak code fixes.)

Cascade code is provided for user in *Typical HEP experiment* -category physics lists.

Models are also available from LHC Computing Grid project (LCG) framework[1].

Optimized Geant4 physics lists (Release PACK 2.4) for high energy physics use contains Bertini cascade in physics lists

- LHEP_BERT,
- LHEP_BERT_HP and
- QGSP_BERT.

[1] J. Beringer, "(p, xn) Production Cross Sections: A Benchmark Study for the Validation of Hadronic Physics Simulation at LHC," *CERN-LCGAPP-2003-18,* CERN (2004).

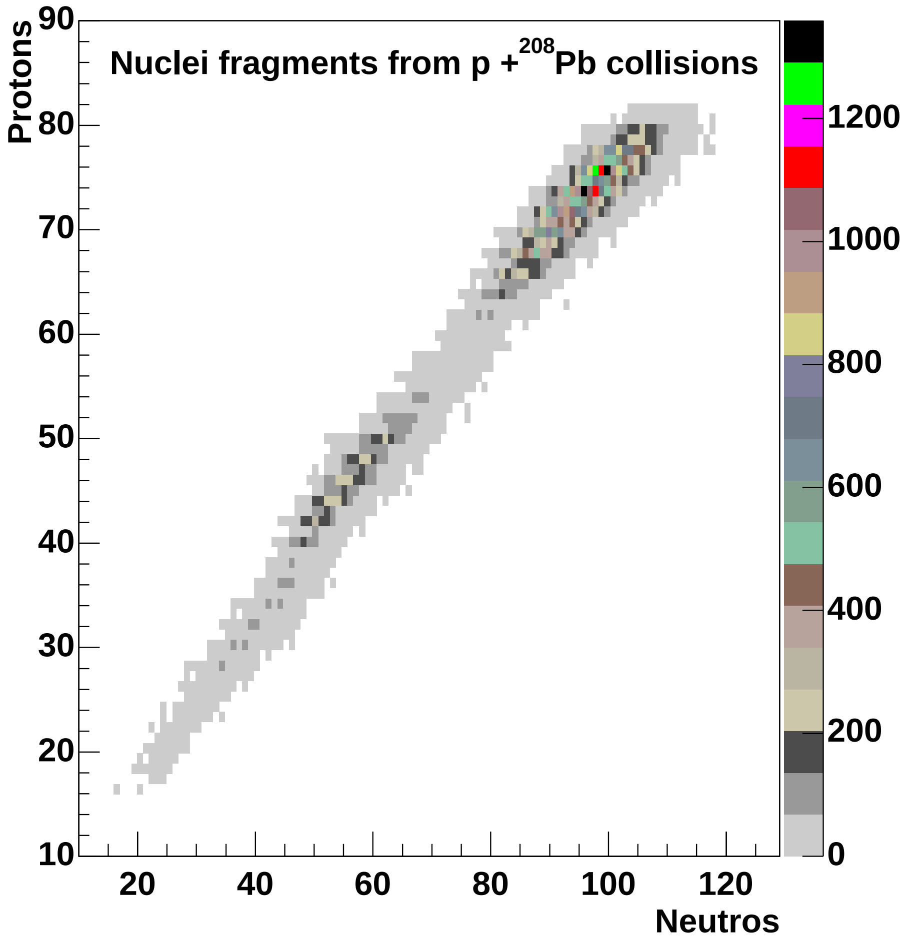
Physics Validation

To validate Bertini isotope production physics performance, we have made extensive Geant4 simulations on proton-induced reactions in Pb and Au targets[1].

[1] A. Heikkinen and T. Linden, “Validation of the GEANT4 Bertini Cascade model and data analysis using the Parallel ROOT Facility on a Linux cluster”, *Proceedings of CHEP04*, Interlaken, Switzerland, 27th September - 1st October, (2004).

Physics Validation

Isotope production from p(1 GeV) + ^{208}Pb collisions with Geant4 Bertini intra-nuclear cascade models.



Physics Validation

Bertini cascade has also been validated in various different fields by several authors:

- BaBar (pion production studies)[1]
- Major validation effort in high energy physics community is done by LCG Simulation Validation Project[2].
- Geant4 hadronic performance for instrumentation in HEP[3] and in space science and medical applications[4] are also estimated.

[1] D. H. Wright , "Using Geant4 in the BaBar Simulation," *SLAC-PUB-9862* (2003).

[2] J. Beringer, "(p, xn) Production Cross Sections: A Benchmark Study for the Validation of Hadronic Physics Simulation at LHC", *CERN-LCGAPP-2003-18*, CERN (2004).

[3] V. N. Ivanchenko, "Geant4: Physics Potential for HEP Instrumentation," *Nucl. Instr. and Meth. A*, **494**, pp. 514-519 (2002).

[4] V. N. Ivanchenko, "Geant4: Physics Potential for Instrumentation in Space and Medicine," *Nucl. Instr. and Meth. A*, **525**, pp. 402-405 (2004).

Conclusions

After extensive benchmarking of the INC physics and sub-models

- Bertini cascade is now reasonably well validated up to 10 GeV incident energy and
- users from various fields are using it successfully.

Currently we are extending Bertini models

- to treat new particles, such as incident kaons and lambdas;
- also, we plan to add optional interfaces to various sub-models,
  (such as elastic treatment), that are already available in current implementation.