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# IMPLEMENTING THE BERTINI INTRA-NUCLEAR-CASCADE IN THE GEANT4 HADRONIC FRAMEWORK

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## ABSTRACT

We have implemented a hadronic intermediate energy Bertini cascade model into a generic detector simulation Monte Carlo program Geant4. Bertini intra-nuclear cascade with exitons, pre-equilibrium, nucleus explosion, fission, and evaporation are modeled and implemented as a hadronic final state generator in the Geant4 hadronic shower framework.

With Object Oriented technology and design we achieve a transparency of the physics. Clear separation of the physics models allows critical analysis, development, and extendibility of models behind various components of the particle emission. The implementation provides effective tools for validating the physics results of classical Bertini model, its variations, and related models.

We present an overview of the design and implementation, and illustrate the cascade model functionality with examples on particle final state cross-sections and isotope production. Also, we report on latest model modifications and extensions.

*Key Words:* Geant4, Bertini cascade

## 1 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.

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 [3] and hadron-nucleus event generator validations made by EDDA Collaboration [4].

Our focus here is to report on general INC framework provided by Geant4 and present an specifi c Bertini cascade implementation based on this interface. Geant4 toolkit [5] offers comprehensive range of tools for model developer, as well as tested functionality for simulating the passage of particles through matter. Large number of various hadronic models are available, from fully parametric models, such as GHEISHA code [6], to highly theoretically driven models, such as CHIPS [7]. Review of these algorithms and physics models behind the hadronic monte-carlo event generators can be found from the Geant4 Physics Reference Manual or from [8].

## 2 BERTINI CASCADE MODELS

In inelastic particle-nucleus collisions a fast phase ($10^{-23}$ – $10^{-22}$ s) of INC results in a highly exited nucleus is followed by fi ssion and pre-equilibrium emission. A slower ($10^{-18}$ – $10^{-16}$ s) compound nucleus phase follows with evaporation. The INC model developed by Bertini solves on the average the Boltzmann equation of this particle interaction problem.

The Bertini nuclear model consist of a three-region approximation to the continuously changing density distribution of nuclear matter within nuclei. 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.

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 [9].

Models included are Bertini INC model with exitons, pre-equilibrium model, nucleus explosion model, fi ssion model, and evaporation model. Intermediate energy nuclear reactions up to 10 GeV energy are treated for proton, neutron, pions, photon and nuclear isotopes.

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.

A more detailed discussion of Geant4 Bertini cascade models is given in [10] and in Geant4 Physics Reference Manual. Comprehensive treatment of the subject of INC and intermediate-energy nuclear hadronic physics can be found from [11].

## 3 IMPLEMENTING BERTINI CASCADE

Geant4 hadronic shower framework [12] follow the Russian dolls approach to implement framework design. Hierarchy of frameworks encapsulate the common logic of a particular use-case, so hadronics Level 4 framework allows concrete implementation of intra-nuclear scattering. It defi nes purely abstract class *G4VIntraNuclearTransportModel*, which implementers of concrete intra-nuclear transport code need to use.

Following the coding guidelines provided by the hadronic framework, Bertini cascade model interface class *G4CascadeInterface* inherits from *G4VIntraNuclearTransportModel* and implements hadronic fi nal state generator. Implementation consists of 34 classes, while most of them are are utility classes for physics models. Table I review the responsibilities of the key classes of the implementation. and relationships with Bertini cascade model classes are demonstrated in Fig. 1.

**Table I: Geant4 Bertini cascade class responsibilities**

| 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 treatment. |
| Exiton model | *G4NonEquilibriumEvaporator* | Integrated with INC model. |
| Explosion model | *G4BigBanger* | |
| Fission model | *G4Fissioner* | Uses *G4FissionConfiguration*. |
| Evaporation model | *G4EquilibriumEvaporator* | Full de-exitation of nuclei. |

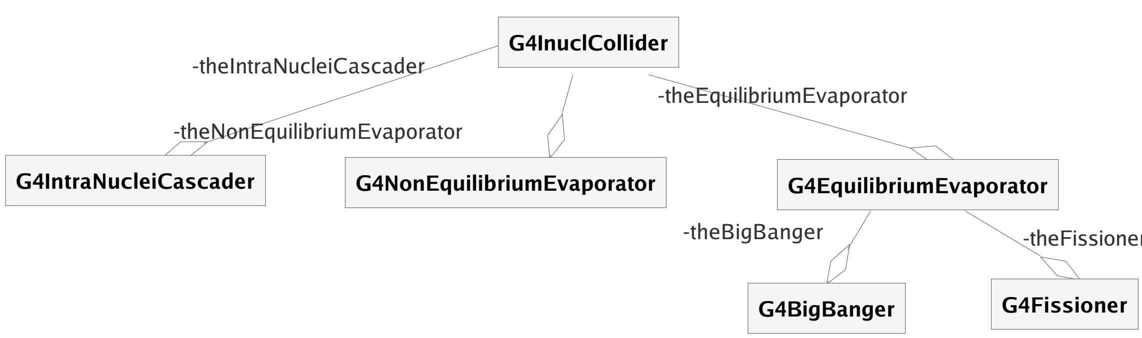


**Figure 1: Unified Modeling Language diagram demonstrating relationships between Geant4 Bertini cascade sub-models classes.**

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 classical Bertini model, its variations and related models.

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. Alternatively models also available from LHC Computing Grid project (LCG) framework [13]. Optimized Geant4 physics lists (Release PACK 2.4) for high energy physics use contains Bertini cascade in physics lists named LHEP_BERT, LHEP_BERT_HP and QGSP_BERT. Detailed information of physics lists can be found from [14].

## 4 PHYSICS VALIDATION

To validate Bertini isotope production physics performance, we have made extensive Geant4 simulations on proton-induced reactions in Pb and Au targets [15]. In comparison with experimental data general features are reasonably well reproduced, Fig. 2 demonstrates Bertini cascade model ability to produce isotopes.

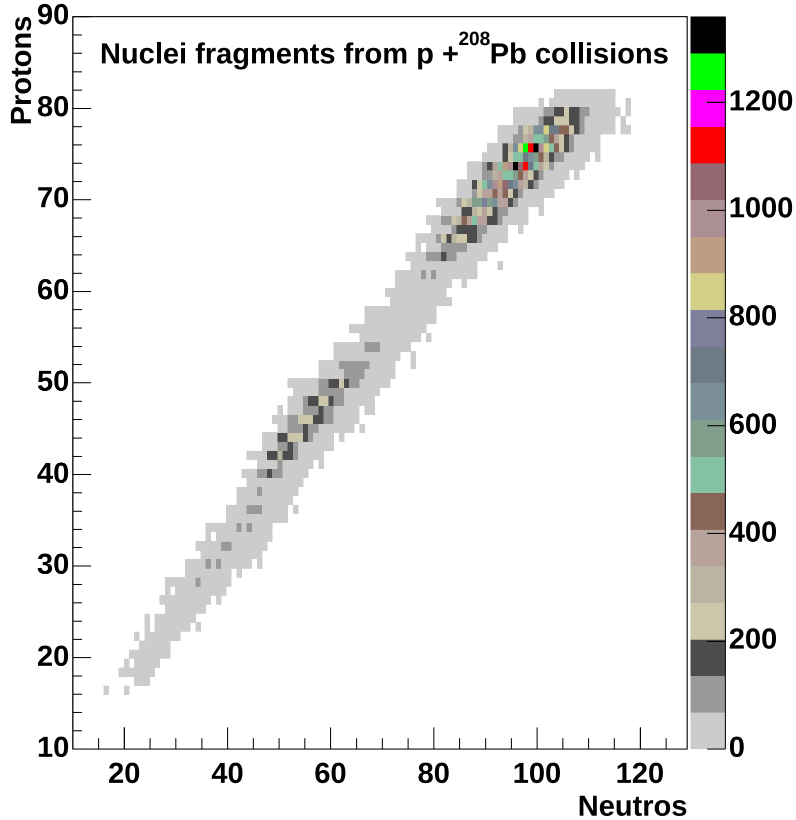


**Figure 2: Isotope production from p(1 GeV) + $^{208}$Pb collisions with Geant4 Bertini intra-nuclear cascade models.**

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

- BaBar experiment was the fi rst large high energy physics experiment to incorporate Geant4 into its detector simulation. In [16] they described series of Geant4 validation tests, and fi nding that cross section for pion production from 730 MeV protons on carbon had large differences between Geant4 Low Energy Parametrized (LEP) model and experimental data. Geant4 LEP model applied is a re-engineering of the GHEISHA code [6], also available in Fortran based Geant3. Repeating the validation test with Bertini model, a much better agreement with the data was achieved at all angles.
- Another major validation effort in high energy physics community is done by LCG Simulation Validation Project [13].
- Geant4 hadronic performance for instrumentation in HEP are evaluated on [17].
- The usefulness of Geant4 Bertini cascade in space science and medical applications has been estimated in [18].

## 5 CONCLUSIONS

The Bertini cascade model in Geant4 simulates the hadronic interactions of protons, neutrons and pions with surrounding materials. Extensive benchmarking of the INC physics provided by Bertini cascade sub-models, exitons, pre-equilibrium state, nucleus explosion, fi ssion, and evaporation has been made. Model is now validated up to 10 GeV incident energy and users from various fi eld are using it successfully.

Since it has already been demonstrated that current Bertini cascade model is performing relatively well, we are extending it currently to treat new particles, such as incident kaons and lambdas. Also, we plan to add optional interfaces to various models, that are available in current Bertini cascade implementation. Thus making validation of Bertini model, its variations, and related models more transparent.

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