BERTINI inter-nuclear cascade implementation in GEANT4

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cascade, pre-equilibrium, fission, evaporation

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GEANT4

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Results and conclusion

GEANT4 5.0 implementation

Bertini intra-nuclear cascade (INC) models

Outline

Bertini intra-nuclear cascade implementation in GEANT4

Alois Heikkilä, Nikita Stepanov, and Johannes Peter Welisch
2002: INVCL++

1999: INVCL code by N. Stepanyan

1970: H.E.G.

1968: H.W. Bertini published standard methods to be used in many INC implementations

1966: extinction model by J.J. Griffin

1958: First computer simulations by N. Metropolis

1948: M. Goldberger made first calculations by hand

1947: INC first proposed by R. Serber

INC background
treatment

• Pre-equilibrium model developed to support low energy

\[ E < 10 \text{ GeV} \]

Physical foundation comes approximate if \( E > 200 \text{ MeV} \) or

• Bertini INC solves the Boltzmann equation on the average

• Physically justified collision: the de Broglie wave length of the incident

Introduction to Bertini INC

Bertini intra-nuclear cascade implementation in GEANT4

Atlas Heikkinen, Nikola Stepanov, and Johannes Peter Wieland
Basics of INC model steps

2. N-N cross sections and region-dependent nucleon densities are uniformly over the projected area of the nucleus.

3. The momentum of the struck nucleon, the type of reaction and four momentum of the reaction products are determined.

4. Exiton model is updated as the cascade proceeds.

5. If Pauli exclusion principle allows and

\[
\mathcal{E}_{\text{particke}} > \mathcal{E}_{\text{cut-off}} = \text{2 MeV}
\]

6. \( E_{\text{particke}} \) is performed to transport the products.
accpeting only secondary nucleons with
Pauli exclusion principle (crosses) is taken into account by

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Nuclear model
Multiple particle production is also implemented

• Pion absorption channels ($\pi^+_{\text{abs}}$, $\pi^-_{\text{abs}}$, etc.)

• Collisions and inelastic collisions ($\nu^0 \rightarrow p$, $\nu \rightarrow n$, etc.)

For pions the ING cross sections are provided to treat elastic cross sections after collisions are sampled from experimental differential angles after collisions are sampled from experimental differential cross sections.

Path lengths of nucleons in the nucleus are sampled according to the local density and to free N-N cross sections.

Cross sections

Helsinki, Nikita Stepanov, and Johannes Peter Welisch.

Atosa Heikkinen, Nikita Stepanov, and Johannes Peter Welisch.
(tabulated with both \( A \) and \( Z \) dependence)

- Parameters of the level density
- Increasing excitation number, leading to a equilibrated nucleus
- INC collisions give rise to a sequence of states characterized by
- Particles and holes (the exiton model proposed by Griiffin)
- Nucleon states are characterized by the number of exited

Pre-equilibrium model
(statistical model features

incorporating binding energy parametrization and fission

DFF

Phenomenological fission model uses potential minimization

Simple explosion model decreases exotic evaporation processes

perm break-up is allowed in extreme cases

Break-up models

\[ E_{\text{binding}} < E_{\text{excitation}} < Z > (Z - A) \]

if \( A > 12 \) and \( 3 < A < 6 \)
\[
\begin{align*}
(\text{followed until } E \gtrless 10^{-15} \text{ MeV}) \\
\text{The evaporation model ends with } \gamma \text{ emission chain}
\end{align*}
\]

\[
(\text{followed until } E_{\text{cut}} = 0.1 \text{ MeV})
\]

\text{The main chain of evaporation model}

\text{often used computational method developed by Dostrowski}

\text{CERN4 evaporation model for cascade implementation adapts}

\text{of the emitted nucleus remaining after the INC (by Weisskopf)}

\text{Statistical theory for particle emission}

\text{Evaporation model}
16K lines in 32 classes (4K lines for testing and documentation)

● Source code in processes/hadronic/models/cascade/cascade

which allows modular implementation

● Implemented in GEANT4 hadronic physics framework

● C++ Version INCL++ is a compact stand alone code

● Bertini INC is based on re-implementation of INCL Fortran code

GEANT4 5.0 Implementation
Apply yourself defined in a class C4Cascadeface.

All the models are used collectively through interface methods
(C4NonEquilibriumEvaporator, C4EquilibriumEvaporator etc.)
(C4IntNucleoCascade, C4Fissioner,
Models are organised into separate classes

GEANT4 hadronic framework

Current implementation is quite loosely connected to the

Interacting Bertini INC models
$X + \rightarrow e^+ e^- + \Lambda^{256 MeV}$

Bertini intra-nuclear cascade implementation in GEANT4

Atlas Heikkinen, Nikita Stepanov, and Johannes Peter Welsh
\[ X + \nu_\theta^{30} \rightarrow e^+ + ^{2\text{He}}_6\text{He} \]
\[
\text{Bertini Intra-nuclear cascade implementation in GEANT4}
\]

\[
\text{X} + \text{Fe}^{26\text{MeV}} \rightarrow \text{X} + \text{Fe}^{26\text{MeV}}
\]
\[ \text{Bertini cascade} \]

\[ X + \theta \text{He}^{150} \rightarrow Fe + \Lambda_{236MeV} d \]
\[
\begin{align*}
\text{X} + \text{p} &\rightarrow \Lambda^\text{W}\text{M} + d \\
\theta &\rightarrow 60^\circ
\end{align*}
\]
\[ \begin{align*}
X + \Lambda^{97}W &\rightarrow p + p + \theta = 120^\circ
\end{align*} \]
\[ X + _{22}^{54} \text{Mg} \rightarrow p + \Lambda + \pi^- + \nu \]

Berline Cascade
\[ X + _{27}^{63}Cl + \nu \rightarrow p d + \Lambda W \, _{9}^{27}d \]
\[ X + ^\nu \text{He} \to p d +^{\Lambda\bar{\Phi}}_{\text{EM}} d \]
\[
\text{X} + \Lambda_{\not 39MeV} + p \rightarrow \text{p} + \Lambda + \gamma + \not \gamma = 135^\circ
\]
We have tested the code in a energy range 60 MeV - 10 GeV

- Particles treated: $\gamma$, $n$, $p$, and nuclear isotopes
- Evaporation are modelled
- Excitons, pre-equilibrium, nucleos explosion, fission, and 

We have released a Berthini INC model in Geant4 5.0

Conclusion