Geant4 Hadronics Overview

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Outline

- Geant4 Hadronic Physics Working Group
- Hadronic model inventory
- Hadronic framework
  - Framework levels, cross sections and physics lists
  - Theory driven models
  - Parametrization driven models
  - Data driven models
- Recent developments
- Future plans

Following items are not discussed here:

- Hadronic physics validation (covered by Dennis Wright)
- Physics lists (Gunter Folger)
- Shower shape issue (Alberto Ribon)
- CHIPS (Mikhail Kossov)

Group Members

- Aatos Heikkinen (Helsinki Institute of Physics) - coordinator
- Dennis Wright (SLAC) - coordinator
- Makoto Asai (SLAC)
- Gunter Folger (CERN)
- Alexander Howard (CERN)
- Vladimir Ivantchenko (ESA, CERN)
- Tatsumi Koi (SLAC)
- Mikhail Kossov (CERN)
- Fan Lei (Qinetiq)
- Maria Grazia Pia (INFN, CERN)
- Alberto Ribon (CERN)
- Nikolai Starkov (CERN)
- Peter Truscott (Qinetiq)

(Hadronic Physics Working Group web-page http://geant4.web.cern.ch/geant4/collaboration/working_groups/hadronic/)

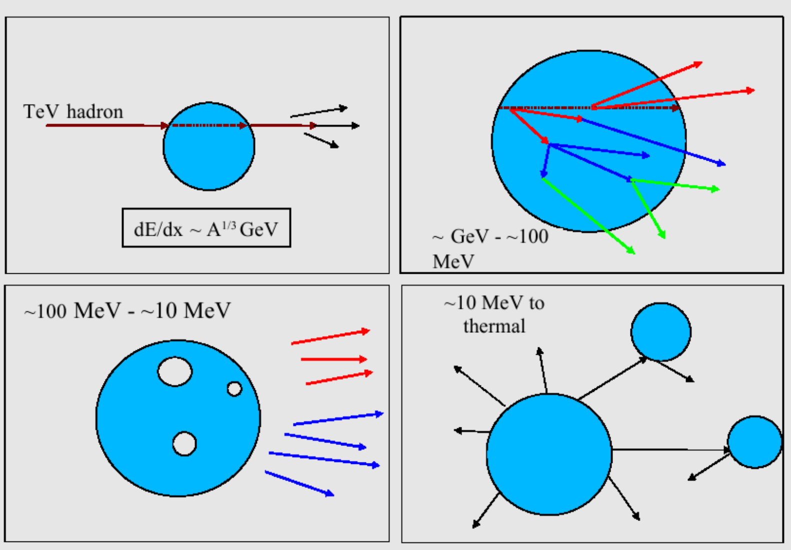
New Group Members

- Giacomo Cuttone (Research Chief at Laboratori Nazionali del Sud, INFN Catania)
- Pablo Cirrone (INFN Catania)
  - Medical applications and **measurements of nuclear fragment production** for C ion on different targets (0-400 AMeV)
  - Participates on behalf of Geant4 to **IAEA initiative to standardize the use of nuclear data** for simulating nuclear interactions in charged particle radiation therapy applications
- Alain Boudard (CEA Saclay) - Original developer of Liegé cascade

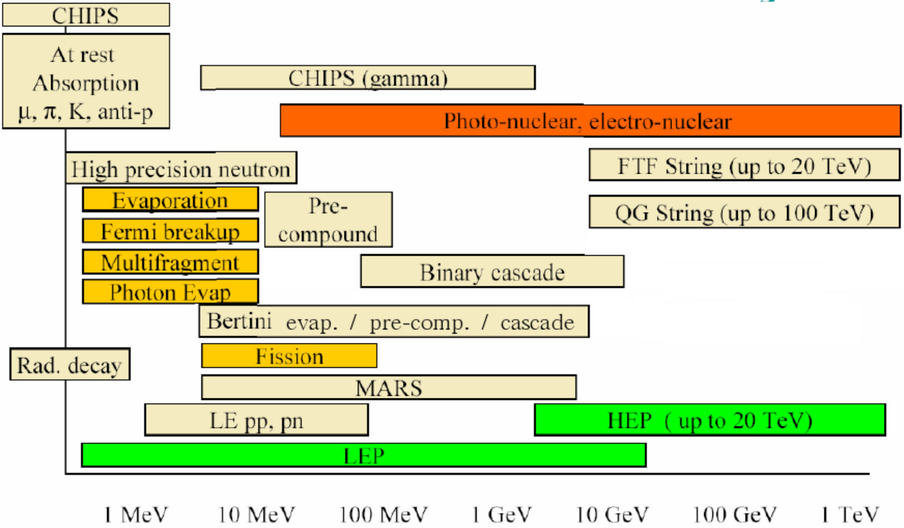
PhD students starting this summer 2007:

- Pekka Kaitaniemi (HIP, CEA) - INCL-ABLA models in Geant4
- Francesco Romano (INFN Catania)
  - Light particle emission from pre-equilibrium and evaporation models
  - Implications to hadronic treatment

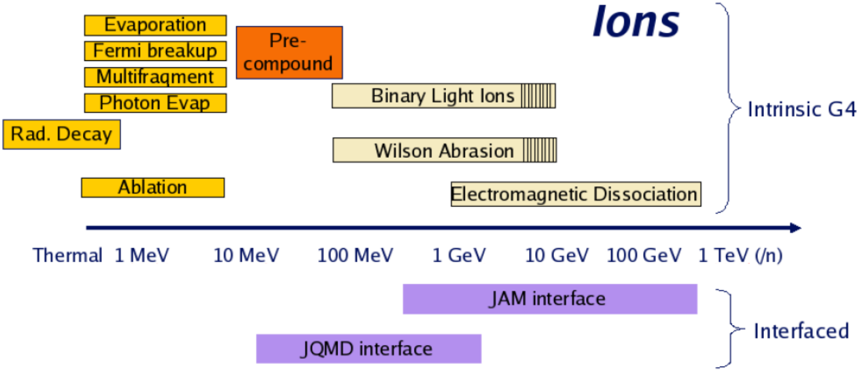
Modeling hadronic physics in keV – TeV energy range



Hadronic model inventory



Existing Geant4 Nuclear-Nuclear Final State Models



EPAX model also compared with above but not interfaced (REAT-MS)

(from T Koi, 28/07/06)

QinetiQ

Model details are documented in Geant4 Reference Manual

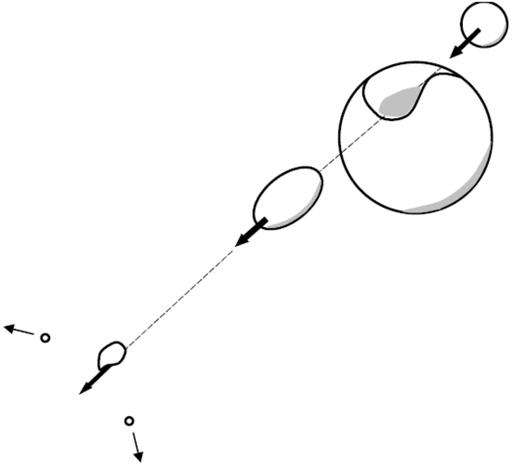


Figure 26.1: In the abrasion process, a fraction of the nucleons in the projectile and target nucleons interact to form a fireball region with a velocity between that of the projectile and the target. The remaining spectator nucleons in the projectile and target are not initially affected (although they do suffer change as a result of longer-term de-excitation).

Wilson abrasion model. (http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/html/)

Modular structure of Geant4 hadronic interactions

- Pure hadronic processes valid 0–100 TeV
- γ μ e - nuclear processes valid 10 MeV – TeV
- Hadron ionization for charged hadrons
- At rest
  - Stopped μ, π K, anti-proton
  - Radioactive decay
- Elastic
  - Same process for all long-lived hadrons (but different models)
- Inelastic
  - Different process for each hadron
  - Photo-nuclear, electro-nuclear, muon-nuclear
  - Ions
- Capture
  - For neutron
- Fission
  - Neutron-induced

Cross sections

- Default cross section sets are provided for each type of hadronic process:
  - Fission, capture, elastic, inelastic
  - Hadronic framework provides mechanism to override or replace these data sets
- Different types of cross section sets:
  - Some contains only a few numbers to parametrize cross section
  - Some represent large databases (data driven models)
  - Some are not yet fully exposed to framework (such as Bertini data)

Alternative cross sections:

- Low energy neutrons
- Neutron and proton reaction cross sections
  - 20 MeV $<$ E $<$ 20 GeV
- Ion-nucleus reaction cross sections

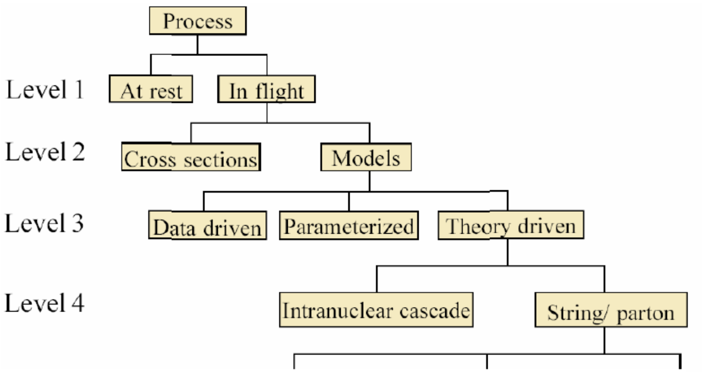
Example: Neutron data files - G4NDL3.10

- External 48 MB set of data derives largely from the ENDF/B-VI library
  - Maintained by Cross Section Evaluation Working Group (CSEWG) http://www.nndc.bnl.gov/csewg/
- Contains cross section data for
  - Elastic, inelastic, and capture processes
  - Thermal scattering
    - Coherent, incoherent, inelastic
  - Isotope production
  - Uranium fission

Also contains data from JENDL library

- Nuclear Data Evaluation Center of Japan Atomic Energy Agency

Hadronic framework - levels



(J.P. Wellisch, Hadronic shower models in Geant4 – the frameworks, Computer Physics Communications 140 (2001) 65–75)

Theory driven models

- Dominated by theory
  - QCD
  - Strings
  - Chiral perturbation theory
- Data used mainly for normalization and validation
- Final states determined by sampling theoretical distributions
- Theory driven models are often CPU intensive
  - With careful optimization, significant speedup may be achieved

Physics lists

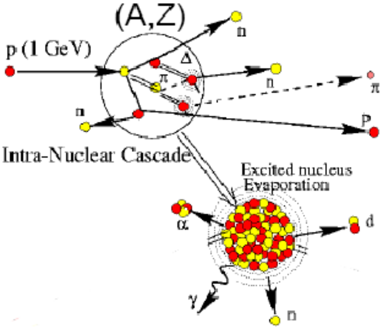
Geant4 philosophy implies the usage of physics lists,
to provide wanted collection of models, such as:

- Parton string models at high energies
- Intra-nuclear transport models at intermediate energies
- Statistical break-up models for de-excitation

(See Gunter Folger talk for further details of physics lists.)

Bertini intra-nuclear cascade as an example of theory driven model

Bertini provides a collection of theory driven models with parametrization features E < 10 GeV



Models included:

- Bertini INC model with exitons
- Internal pre-equilibrium model
- Nucleus explosion model
- Fission model
- Evaporation model

(Bertini models are provided in the following physics lists: LHEP_BERT, LHEP_BERT_HP, QGSP_BERT, and QGSP_BERT_HP).

Parametrization driven models

- Depends strongly on both data and theory:
  - Enough data to parametrize cross sections, multiplicities, angular distributions
- Final states determined by theory:
  - Use conservation laws to get correct charge, energy, etc.
- Examples:
  - Fission
  - Capture
  - GEISHA based models

GEISHA as an example of parametrization driven model

Based on GHEISHA package of Geant3.21, two sets of models exist for inelastic scattering of particles in flight:

- Low energy models (LEP):
  - E $<$ 40-50 GeV
- High energy models (HEP):
  - 50 GeV $<$ E $<$ O(TeV)
- Original approach to primary interaction, nuclear excitation, intra-nuclear cascade and evaporation is kept
- Fission, capture and coherent elastic scattering are also modeled through parametrized models

Data driven models

- Characterized by lots of data:
  - Cross section (data tables in code)
  - Angular distribution
  - Multiplicity
- To get interaction length and final state, models simply interpolate data:
  - Usually linear interpolation of cross section, and Legendre polynomials
- Examples:
  - Coherent elastic scattering (pp, np, nn)
  - Radioactive decay
  - Neutrons ($E < 20$ MeV) (separate database is provided)

Recent developments

- Hadronic shower shapes
  - After significant validation, we now understand this issue better, and can provide physics lists with improved performance
  - *See Alberto Ribon talk for further details shower shape status*
- CHIPS
  - Improved modeling for stopping particles etc.
  - *See Mikhail Kossov talk for further details*

Recent developments - cascade models

Both Bertini and Binary cascade models have undergone extensive validation (particularly for 100 MeV - 1 GeV energies)

- Bertini cascade
  - *Models based on INUCL code*
  - Cascade has been extended to projectiles with strangeness
  - Upgraded to handle elastic scattering
    - (G. A. P. Cirrone et al.,*Systematic validation of Geant4 electromagnetic and hadronic models against proton data*, CHEP 2006, http://www.hip.fi/geant4/refsHeikkinen/heikkinen06eTalk.pdf)
- Binary cascade
  - *Model based on hadron collisions with nucleons, which form resonances decaying according to their quantum numbers*
  - Extended to include light ion-ion collisions, A $<$ 13

Recent developments - elastic scattering

- Elastic scattering
  - *Derived from the GHEISHA code of Geant3*
  - *Problem*: Tends to over-estimate scattering at large angles, ($>$ 15 *degrees*)
  - A better model has been developed:
    - Relativistically correct
    - Includes coherence effects, such as diffraction minimum due to the nuclear radius
    - Removes charge exchange as a separate reaction
    - Includes improved p and n scattering from p, d, and He targets
    - High precision neutron elastic scattering from isotopes

(D. Wrigth et al.: *Recent Developments and Validations in Geant4 Hadronic Physics*, SLAC-PUB-12348. http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12348.pdf)

Recent developments - LEP, HEP models

- LEP, HEP
  - *Models are derived from the GHEISHA*
    - *Problem*: Originally formulated as a shower code, they do not conserve energy momentum, charge or other quantum numbers on an event-by-event basis
  - Recent improvements:
    - Improved charge and baryon number conservation, especially for hadron collisions with light nuclei.
    - Better energy conservation

Recent developments - LEP, HEP models

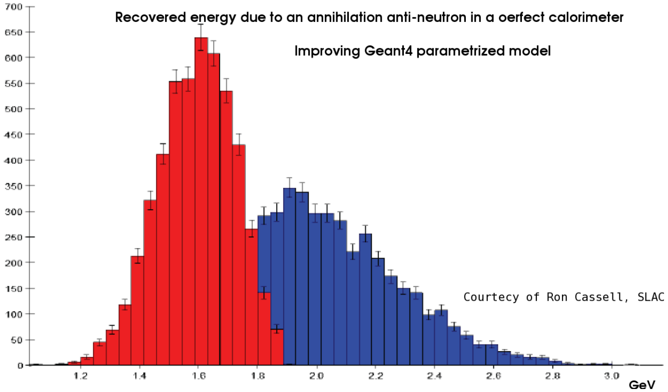


Figure. E_{tot} *recovered from a 50 MeV anti-neutron coming to rest in a perfect calorimeter.*

Original version (blue): *recovered energy has mean at 1.9 GeV, but broad tails are present.*

The new model (red): *enforces the correct 1.93 GeV upper limit, making energy accounting possible.*

Hadronic physics plans (1/3)

Priorities of Geant4 hadronic physics development for the year 2007 are:

- Solving hadronic **shower shape issue**
- Continue validation of existing models and provide support for optimal set of validated physics lists
- Inclusion of new Fritiof fragmentation (FTF) diffraction model
- First release of INCL4-ABLA models
- Improved coupling of binary cascade to pre-compound model
- Completion of Glauber-Gribov cross sections
- Bertini cascade:
  - Sub-model interfaces provided
  - Improvement to Coulomb barrier treatment
- Deliver first version of charge exchange process release
- **New parametrized model using HARP data**

Hadronic physics plans (2/3)

- CHIPS
  - Low energy simulation of anti-proton - nuclear interactions
  - Upgrade of photo- and lepto-nuclear single nucleon production
- Coherent elastic hadron scattering from nuclei
  - Prepare a generator of quasi-elastic hadron-nucleus scattering
- Extend pion cross sections
  - Include more pions and kaons in final state
- Error reporting capability based on hadronic whiteboard to be completed

Hadronic physics plans (3/3)

Moreover Geant4 hadronic physics working group will:

- Continue participating HSSW **benchmarking and code comparisons**
    - As decided in the Hadronic Shower Simulation Workshop, Fermilab, September 2007
- Provide improved recommendations on choosing optimal sub-model from various available options
    - Workshop in June 2007 for pre-equilibrium and evaporation models
- Participate International Atomic Energy Agency (IAEA) standardization initiative
- Improve hadronic framework usage (for example Bertini cascade) and code re-use of sub-models (INCL)
- **Optimize the code speed**
    - For example, we received factor ≈ 2 speedup of Bertini INC after **optimization performed by computer specialists** at High Performance Computing Unit, Abo Akademi University, Finland

Future Geant4 hadronics attractions: Liége cascade

INCL4-ABLA Range of application

Beams: π,p,n,d,t,3He,4He
Energies: ~100 MeV- 3 GeV
Targets: Al (C?) - U

Precisions: 10%-20% except identified defects
((p,n) quasielastic, π production, light nuclei…)

Already in transport codes (LAHET-MCNPX-Hermes)

INCL5-NewABLA Improvements

Low energy (down to 50 MeV?)
π production, π beams
Light evaporation residues, light nuclei

All parts separately tested, to be assembled soon
(International Comparison of Spallation Models; late 2007)

Future

Extension up to ~10 GeV
Beams of light ions

Note: (Models to be complemented by coherent scattering (Glauber type) and nuclear structure at low energy)

As experimentalists, a real will (or wish) to have it in GEANT-4

(A. Boudard)

Potential of INCL5 for light nuclear-nuclear physics

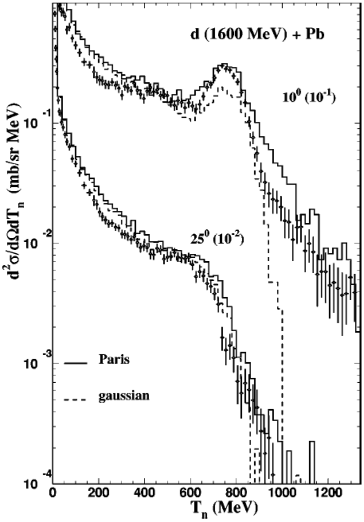
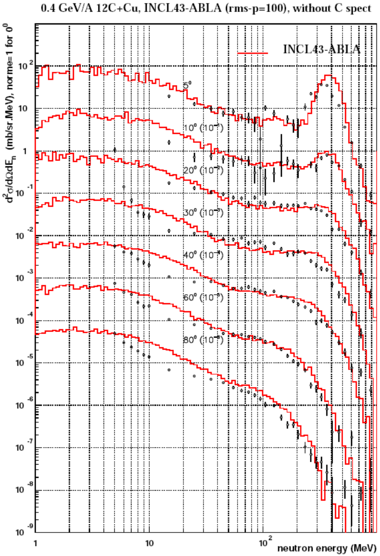


FIG. 22. Neutron double differential cross sections for deuteron-induced reactions on a Pb target at 800 MeV per nucleon incident energy, plotted with a linear energy scale. The predictions of the INCL4 + KHSv3p model are given by the histograms. Two mo-



(A. Boudard et al.)