Geant4 11.1.p02 and
Hadronic Physics Status

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On behalf of the Geant4 Hadronic Physics Working Group

Geant4 Technical Forum, 28 September 2023

1st part: G4 11.**1**.p0**2**

Main Changes in Hadronics *vs.* G4 11.1.p01 (1/2)

- *particles/*
  - Updated mean lifetime values of *G4XicZero* and *G4AntiXicZero* according to values in PDG-2022
  - Corrected mean lifetime values for *G4OmegacZero* and *G4AntiOmegacZero*
- *hadronic/models/cascade* (BERT)
  - *G4BigBanger* : added protection in the method *generateBangInSCM()* to avoid very rare cases of unphysical negative energy of one of the secondaries produced by the Bertini model
    - The problem was reported by ATLAS in production runs based on release 10.6 ; the secondaries with negative (both total and kinetic) energy were always neutrons, produced by the internal Bertini nuclear de-excitation, after the intra-nuclear cascade.
- *hadronic/models/particle_hp/*
  - Added *G4ParticleHPNucLevel* : new data structure for nuclear levels
  - *G4ParticleHPDeExGammas* : use *std::vector* instead of C-arrays
  - *G4ParticleHPInelasticBaseFS* , *G4ParticleHPInelasticCompFS* : gamma cascade sampling is checked and simplified (removed unnecessary computations)

Main Changes in Hadronics *vs.* G4 11.1.p01 (2/2)

- *hadronic/models/util/*
  - *G4Fragment* : replaced *G4HadronicException* with standard *G4Exception*
    - In the method *CalculateMassAndExcitationEnergy()* , replaced the fatal *G4HadronicException* with an *EventMustBeAborted* exception to avoid rare crashes seen in INCLXX, which are difficult to reproduce and fix...
- *hadronic/models/inclxx/*
  - *G4INCLNNToNLK2piChannel* : fixed bug in the method *fillFinalState()*

Note : these fixes do not affect hadronic showers

2nd part: Status of Hadronics

Hadronic String models

- So far, FTF and QGS string models are unchanged with respect to G4 11.1
  - Effort went to study the problem of too narrow/optimistic energy resolutions predicted by Geant4 for ATLAS HEC and TileCal test-beams
    - Good agreement up to G4 10.4 ; then, ~20% too optimistic energy resolutions
    - Comparisons with Fluka, using the new interface between Fluka-Cern and Geant4, show close agreement with Geant4
      - This could indicate that the development in Geant4 string models − driven by thin-target − did improve the accuracy of these models, while the increased disagreement with test-beam data is due to something else missing/wrong/inaccurate in the simulation of the test-beam set-ups...
    - Found a new tune of the FTF model parameters which reproduces well the energy resolutions of ATLAS HEC and TileCal test-beams – *i.e.* similar to the old simulations up to G4 10.4
      - This new tune enhances the occurrence of the quark-exchange process in string formation, and the destruction of the target nucleus, with respect to the “default” set of FTF parameters
    - Work by Lorenzo Pezzotti, Dmitri Konstantinov, A.R.

Intra-nuclear Cascade Models

- **BERT** (Bertini-like cascade)
  - Stable
    - The most used, workhorse cascade model in HEP
- **BIC** (Binary Cascade)
  - Stable
    - Used in medical physics, and sometimes in HEP for evaluating systematic errors
- **INCLXX** (Liege cascade)
  - **Extension to anti-proton annihilations**
    - Annihilation at rest included in G4 11.2.beta; in-flight will be added in G4 11.2
    - Great interest of the CERN AD experiments and some astroparticle experiments for low-energy anti-baryon annihilations
    - Implementation by Ph.D. student Demid Zharenov (supervised by J.C. David), CEA Saclay

Nuclear De-excitation

- New, improved **Fermi Break-Up** model
  - Driven by the long standing issue #2263 (reported by Igor Pshenichnov)
    - Wrong distributions of fragments for light ion interactions (medical and space applications): in general, physically, one expects that the higher the excitation energy the wider the list of open decay channels, and, hence, the larger fragment multiplicity. This was indeed correctly observed in G4 9.2, but not any longer in more recent versions of Geant4 (*e.g.* 10.4).
  - Higher number of fragments are now handled
  - Many more reaction channels are now considered
    - 5421 (now) *vs.* 991 (before)
  - Will be included in G4 11.2
- Technical improvements
  - For initialization
  - For print-out
  - For modern C++, more robust code, clean up and better comments

- Implementation by Vladimir Ivanchenko, in collaboration with J.M. Quesada

Charge-Exchange Process

- Motivations
  - As background for searching new physics in NA64 experiment at CERN
    - A more accurate description is needed with respect to what is currently available in Geant4
  - As a possible refinement of the simulation of hadronic showers in calorimeters
- Charge mesons + nucleons → neutral mesons + nucleons
  - π^- p → π°/η° n , π^+ n → π°/η° p
  - K^- p → K° n , K^+ n → $\underline{K}^\circ$ p
  - Note: some of these processes are already partially included in the existing inelastic hadronic process – *e.g.* by the FTF string model and by the BERT intra-nuclear cascade model – so a separate process needs to be carefully evaluated to avoid "double counting"…
- New cross section class and revised final-state model class will be available in G4 11.2, but not used by default in any physics list
  - Implemented by Tim Lok Chau – CERN summer student supervised by V. Ivanchenko

Interface to (Fortran) Fluka-Cern

- New extended hadronic example, ***FlukaCern***
  - Showing how to use the new Geant4-FLUKA interface to get inelastic cross sections and final-states from Fortran Fluka-Cern
  - Available in G4 11.2.beta (will be also included in G4 11.2)
  - Work by Gabrielle Hugo (Fluka-Cern team)

Coupling ABLA with Cascade and String models

- **ABLA** is an alternative nuclear de-excitation model available in Geant4
  - With respect to the Precompound/de-excitation used everywhere
- Up to G4 11.1, it was possible to couple ABLA only to INCL;
  since G4 11.2.beta, it is possible to couple ABLA to other hadronic models:
  - Intra-nuclear cascade models – BERT and BIC
  - String models – FTF and QGS
- Created also a new “experimental” reference physics list, QBBC_ABLA
  - Similar to QBBC, but with ABLA coupled to BERT, BIC, FTF and QGS, for the four most common hadron projectiles: pion+, pion-, proton and neutron
  - “Experimental” here means that it is mainly for developers, for testing purposes, therefore not yet recommended for users

QMD (Quantum Molecular Dynamic) model

- Current status: physics constructor *G4IonQMDPhysics* for ion interactions used in *Shielding* physics list, with QMD utilised in the range 0.1 – 10 GeV
  - The model has been stable since a number of years, with only a few bug fixes
- Recently, an active development has started, aimed to improve the model, mostly driven by medical physics applications
  - Contributors: Akihiro Haga, Dousatsu Sakata, Yoshihide Sato (Japan)
    David Bolst, Susanna Guatelli, Edward C. Simpson (Australia)
  - Three lines of improvements:
    - Updating the Skyrme-type interaction
    - Forming a realistic initial state of nuclei involved in the collision
      - Alpha-cluster structure : 12C — 3 alpha clusters ; 16O — 4 alpha clusters
    - Finding the best model parameters
  - Integration expected for Geant4 11.2

Development and implementation of new Geant4 QMD model and its validation

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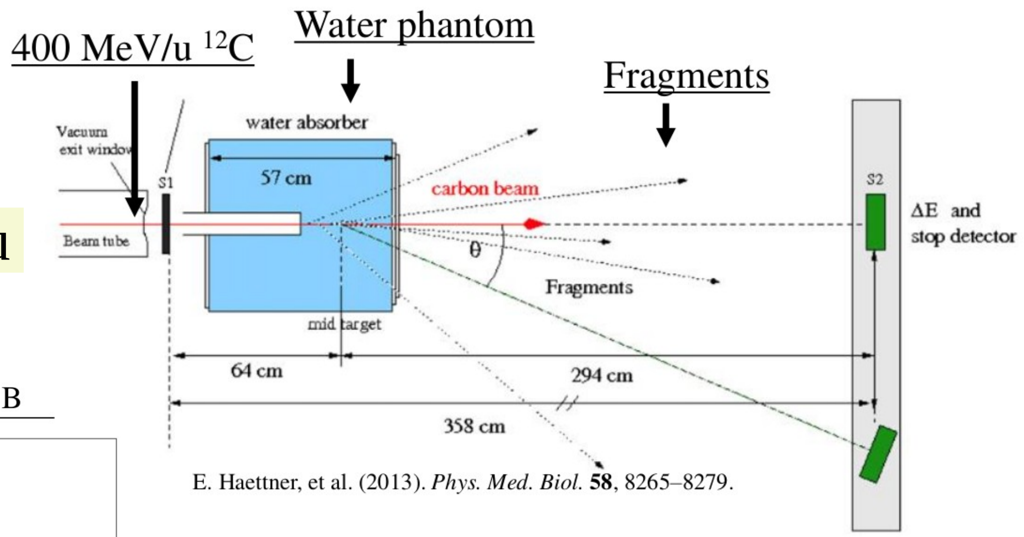
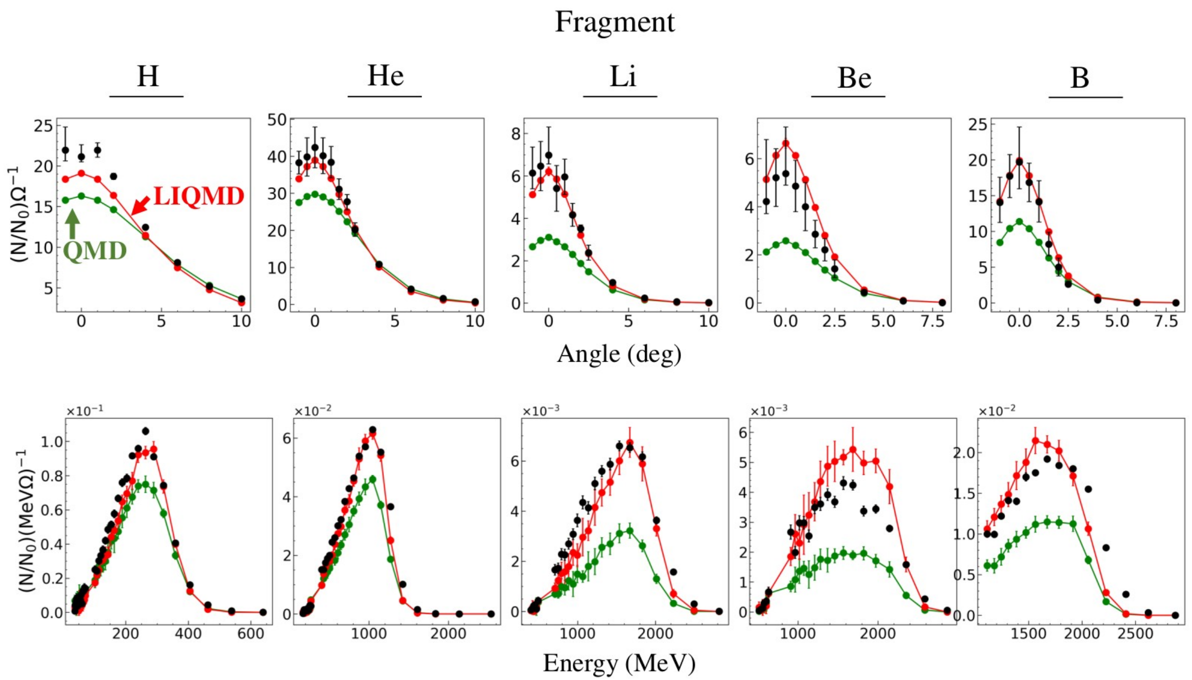


E. Haettner, et al. (2013). *Phys. Med. Biol.* **58**, 8265–8279.

Recommended energy range: 30 – 500 MeV/u



DBRC (Doppler Broadening Rejection Correction)

- Introduced in ParticleHP a new accurate modeling of neutron elastic resonant scattering in heavy nuclei by the use of DBRC algorithm
  - Major improvement made by Marek Zmeskal and Loic Thulliez (CEA Saclay)
  - Relevant for the detailed simulation of nuclear reactors
    - Making Geant4 another step closer to MCNP and TRIPOLI
- Available in G4 11.2.beta (will be also included in 11.2)
  - By default, it is switched off
  - It can be switched on, and its parameters can be set, via UI commands
    - */process/had/particle_hp/**use_DBRC***
    - */process/had/particle_hp/**SVT_E_max** value*
    - */process/had/particle_hp/**DBRC_A_min** value*
    - */process/had/particle_hp/**DBRC_E_min** value*
    - */process/had/particle_hp/**DBRC_E_max** value*

New "_HPT" Physics Lists

- For a precise modeling of thermal neutrons, *i.e.* with kinetic energy **< 4 eV** , a special treatment of neutron elastic scattering is needed
  - Called **Thermal Scattering Law (TSL)**, based on the **S(α, β) approach**
- This is not activated in any of our HP-based reference physics lists
  - But it can be done easily: *physicsList → RegisterPhysics(new G4ThermalNeutrons);*
- Created new "_HPT" physics lists with neutron thermal scattering activated
  - QGSP_BIC_HP**T** : new explicit physics list
  - 7 other P. L. available only via the physics list factory (*i.e.* by setting PHYSLIST)
    - FTFP_BERT_HP**T** , QGSP_BERT_HP**T** , FTFP_INCLXX_HP**T** , QGSP_INCLXX_HP**T** , QGSP_BIC_AllHP**T** , Shielding_HP**T** , ShieldingM_HP**T**
      - For consistency, introduced the aliases Shielding_HP (= Shielding), ShieldingM_HP (= ShieldingM)
- Available in G4 11.2.beta (will be also included in 11.2)

Code review of the ParticleHP package

- Aimed to avoid duplications, improve and modernize the old C++ code, be consistent with what is done – *e.g.* for initialization and multi-threading – in other physics models. Goal is code maintainability & CPU performance
  - There are concerns about the code quality and computing performances
  - Except for few, deliberate cases, mostly involving nuclear de-excitation, no changes are expected on the physics results
    - In G4 11.2.beta, physics results are expected to remain unchanged for all HP physics lists – although only a limited physics validation has been carried out so far
    - For G4 11.2, a more extensive physics validation by experts will be required. We are thinking to share all the technical changes – expected not to impact physics results – among all HP-based physics lists, whereas applying those changes that can affect the physics results in only one HP-physics list (*e.g.* QGSP_BERT_HP)
    - Given that Radioactive Decay is enabled in all HP-based physics lists, some code changes have also been made in the Radioactive Decay model to keep consistency with the implementation of both HP and nuclear de-excitation models
  - Work by Vladimir Ivanchenko