Benchmarking Hadronic Models in Geant4 for Detector Simulations

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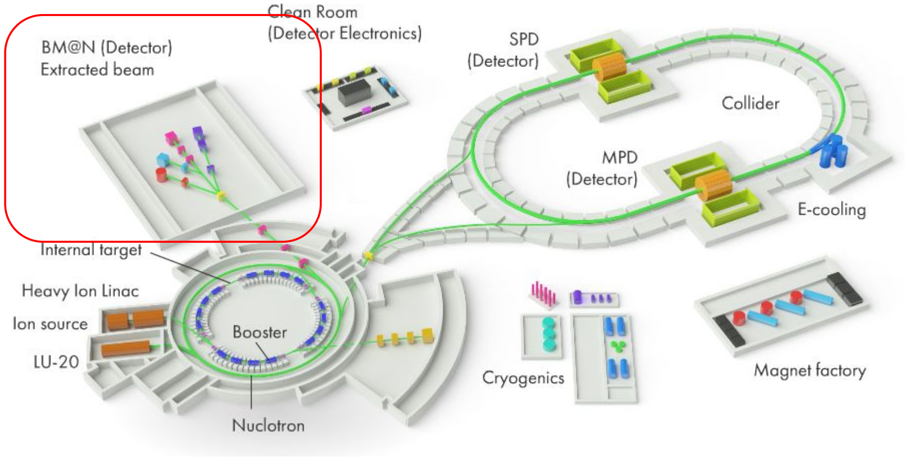
Outline

- Introduction: HGND detector in the BM@N experiment at NICA
- Monte Carlo modelling of the HGND prototype
- Comparison of the detector modelling with different hadronic models:
    - Energy profiles
    - Secondary nuclei
- Conclusions

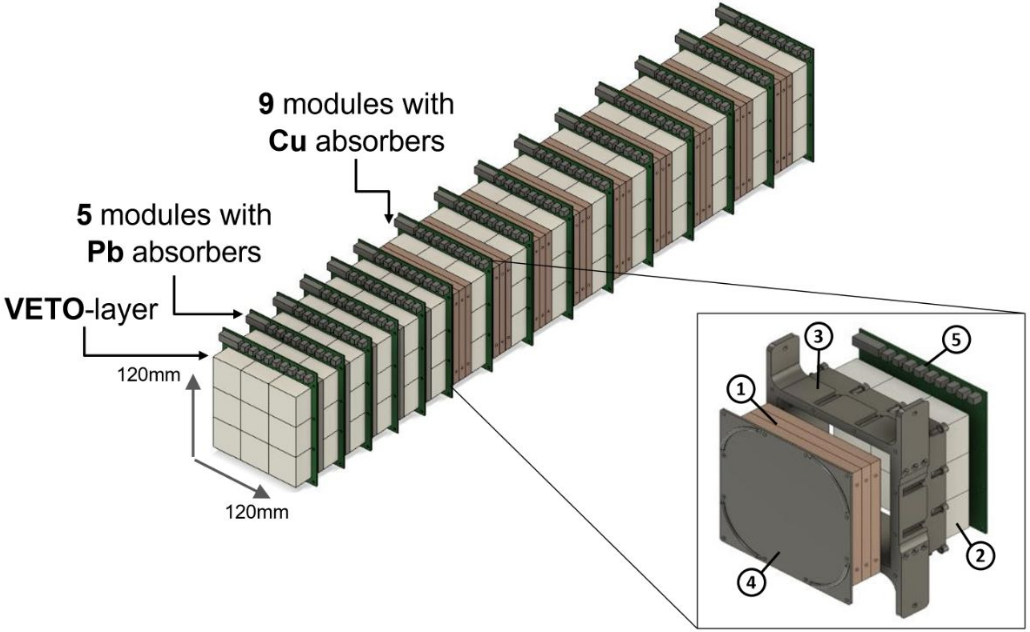
The BM@N experiment at NICA, Dubna

- Heavy ion (Xe^{124}) beam in fixed target geometry with up to 4A GeV kinetic energy.
- The research program of the experiment includes the studies of equation of state and reaction dynamics, for which the collision geometry determination is important.
- Therefore the robust simulation is critical for the design, evaluation and calibration of the detector.
- BmnRoot framework based on Geant4 is used.



Highly Granular Neutron Detector in the BM@N experiment

- Highly Granular Neutron Detector (HGND) is a detector used by BM@N for registration of 0.3 – 4 GeV neutrons.
- A prototype of the detector has been created and tested in a BM@N run.
- For a reliable modelling of the detector response it is important to understand the difference in results obtained with different hadronic interaction models.
- Possible differences will contribute to the systematic uncertainties of measurements with HGND.



A.Zubankov et al., Performance study of the Highly Granular Neutron Detector prototype in the BM@N experiment, arXiv:2503.12624
In print, Nucl. Science Techn., 2025

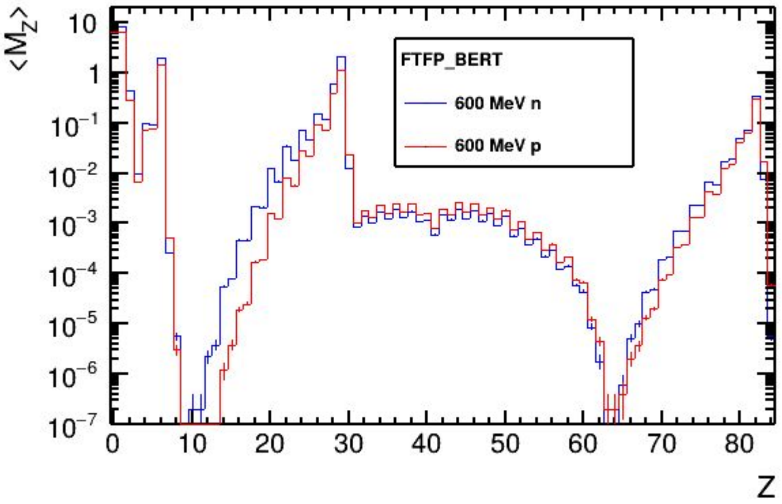
Monte Carlo modeling of the HGND prototype

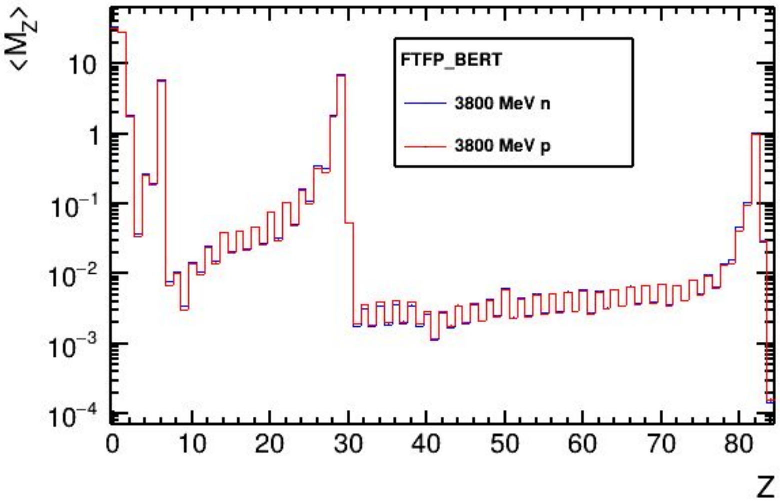
- Neutrons and protons with kinetic energy of 600 MeV and 3800 MeV propagating along the main axis of the the HGND prototype were modelled with Geant4 v11.2.
- Two Reference Physics Lists were employed: FTFP_BERT and QGSP_BIC.
- Bertini intranuclear cascade (BERT) is used in modelling with FTFP_BERT to simulate neutron and proton induced reactions up to 6 GeV. A smooth transition from BERT to Fritiof parton model (FTFP) is employed between 3 and 6 GeV.
- Binary Light Ion Cascade (BIC) is used in modelling with QGSP_BIC to simulate neutron and proton induced reactions up to 6 GeV.
- BIC is used to simulate nucleus-nucleus collisions up to 6 GeV in both Physics Lists.

J. Allison et al., Recent developments in Geant4, Nucl. Inst. Methods Phys. Res. Sect. A **835** (2016), 186-225

https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsListGuide/fo/PhysicsListGuide.pdf

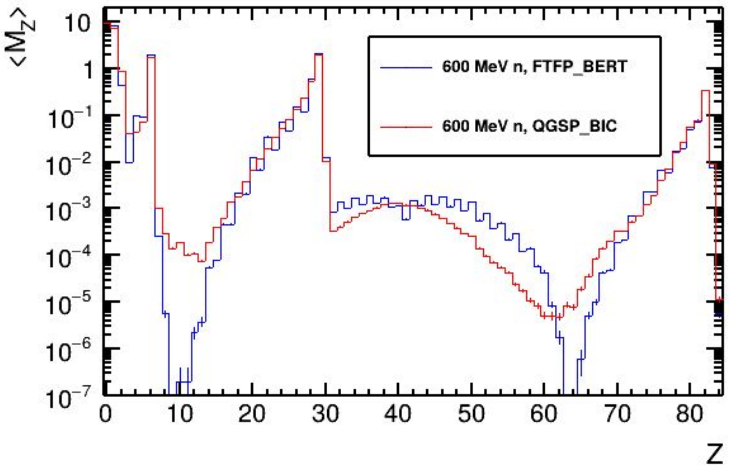
Comparison of multiplicity of secondary nuclei produced in the HGND prototype by neutrons and protons (FTFP_BERT)

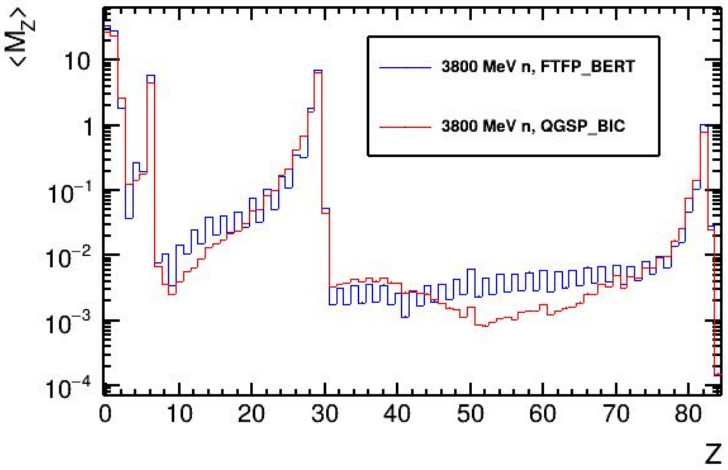




- Slight difference is seen at initial energy of 600 MeV.
- Identical distributions at initial energy of 3800 MeV.
- Only neutrons are considered in the following.

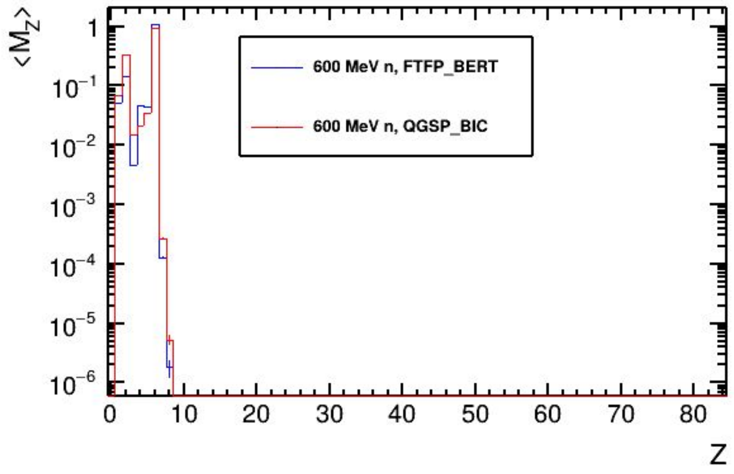
Comparison of multiplicity of secondary nuclei produced in the HGND prototype by neutrons (FTFP_BERT vs QGSP_BIC)

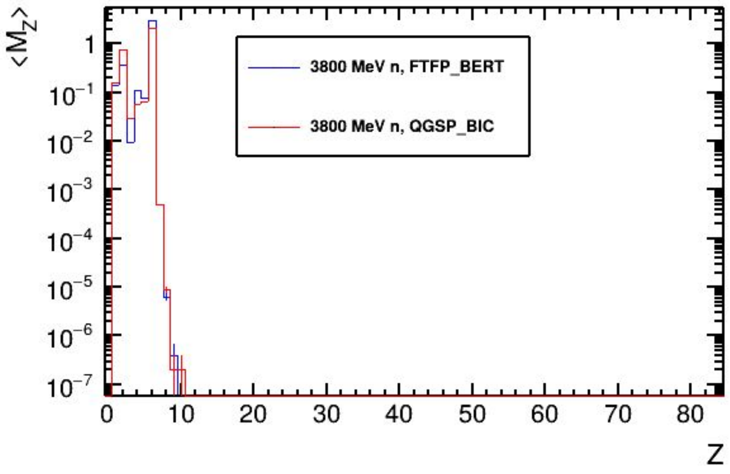




- Much more fragments with 7<Z<14 are produced with QGSP_BIC compared to FTFP_BERT by 600 MeV neutrons.
- This difference is less prominent for 3800 MeV neutrons.

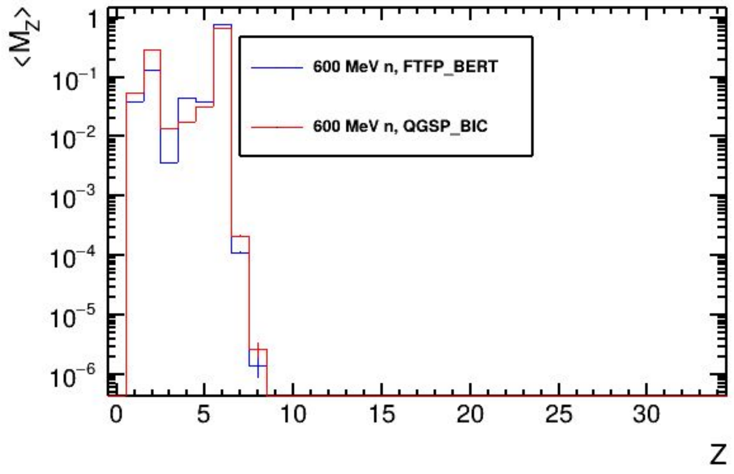
Secondary nuclei produced in the lead absorber layers and transported to the next scintillator layers

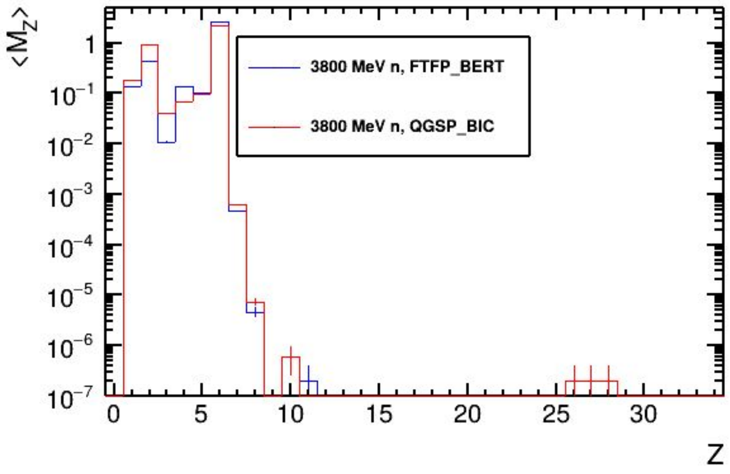




- Fragments with Z>7 do not propagate to the scintillator layers. This compensates the difference between models.

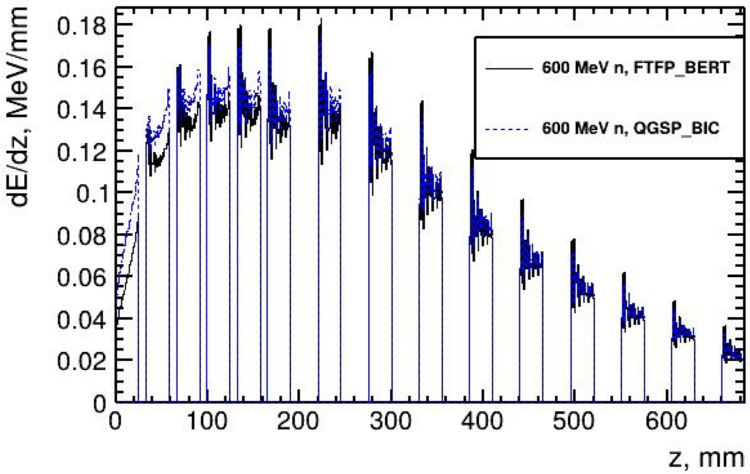
Secondary nuclei produced in the copper absorber layers and transported to the next scintillator layers



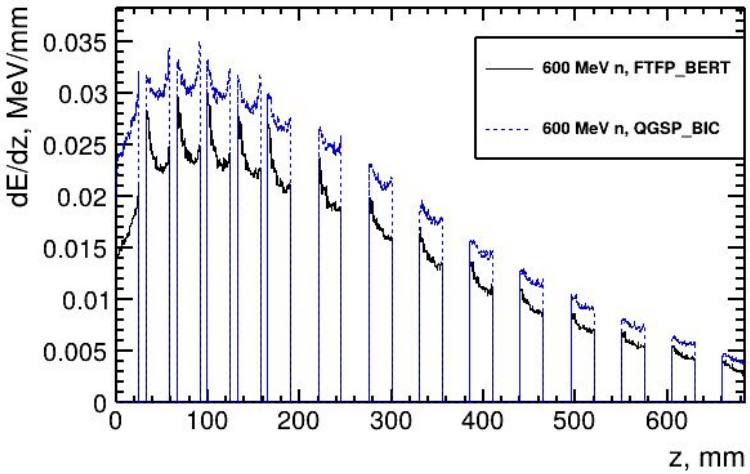


- Fragments with $Z > 7$ do not propagate to the scintillator layers. This compensates the difference between models

Energy deposition profiles from 600 MeV neutrons



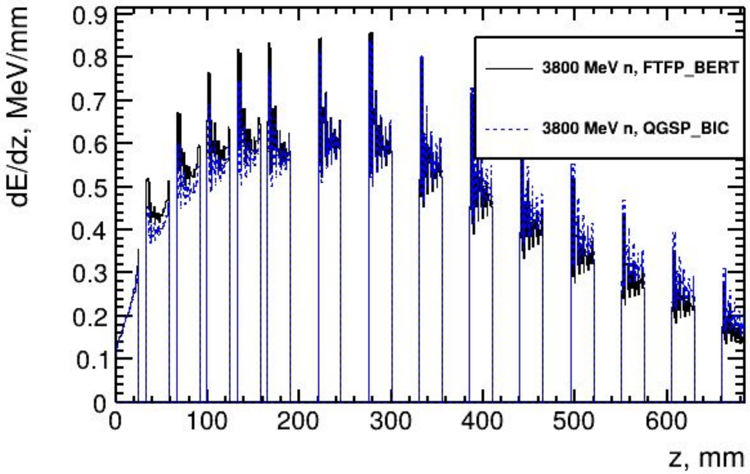
Total



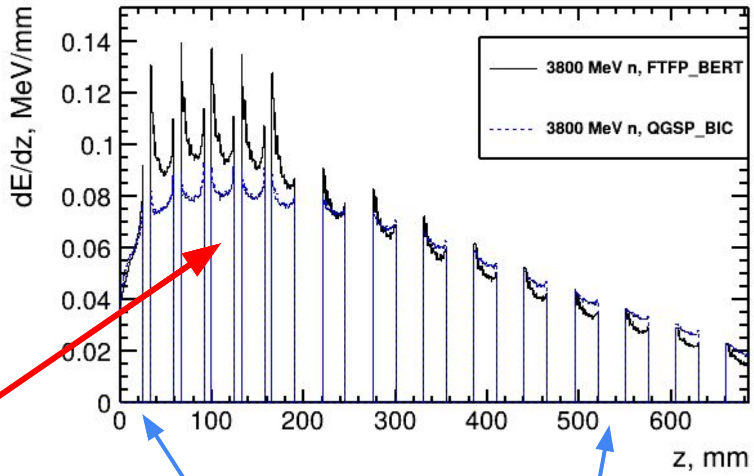
Secondary nuclei

- More energy (up to 20%) is deposited by secondary nuclei while using QGSP_BIC (including the VETO layer)

Energy deposition profiles from 3800 MeV neutrons



Total



Secondary nuclei

- More energy is deposited by nuclei in the scintillator layers after the lead absorbers while using FTFP_BERT
- Less difference between the results of FTFP_BERT and QGSP_BIC in the VETO layer and the scintillator layers after the copper absorbers.

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Conclusions

- Deposited energy profiles in the HGND prototype depend on the choice of the Geant4 hadronic models.

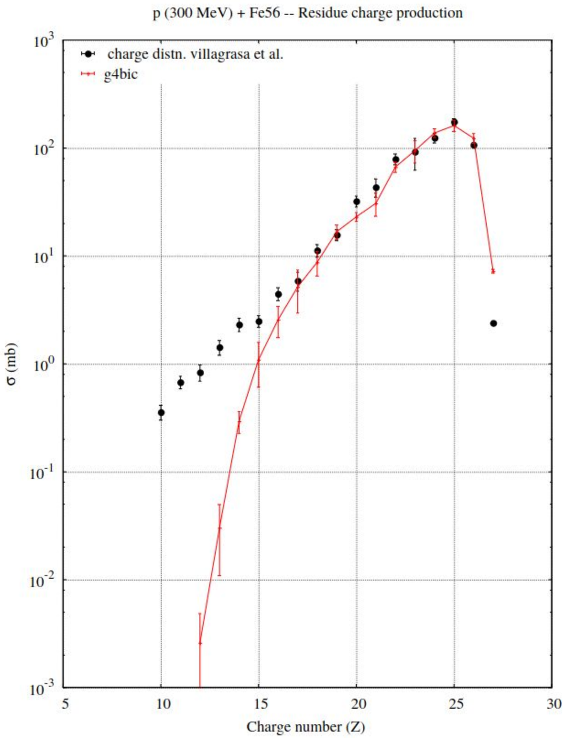
- Using Binary cascade model results in noticeably higher production of IMFs in absorber material, especially for lower-energy primary particles. However, these fragments do not propagate to the scintillator.

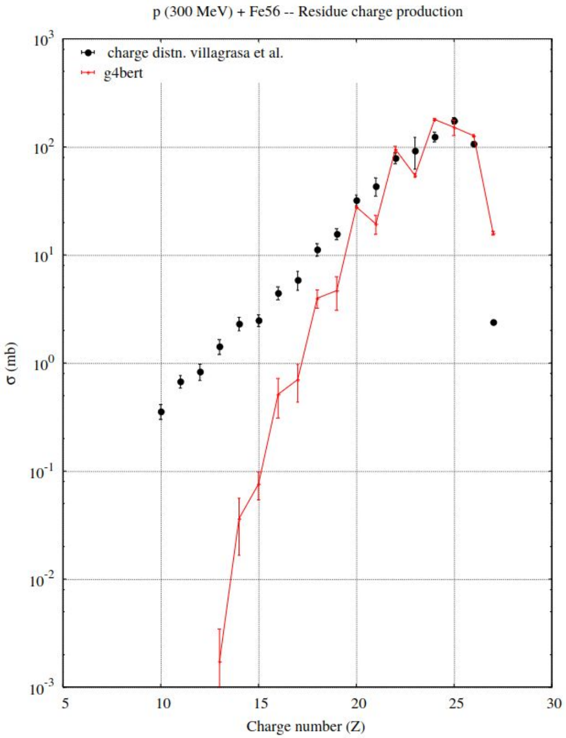
- The measurements of the HGND energy profiles can be proposed as a benchmark for Geant4 hadronic interaction models.

Thank you for your attention!

Backup

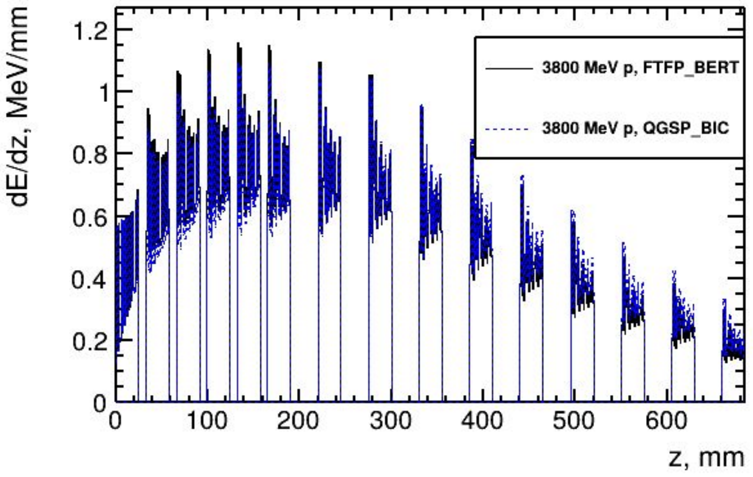
Binary cascade vs Bertini cascade, IAEA spallation data



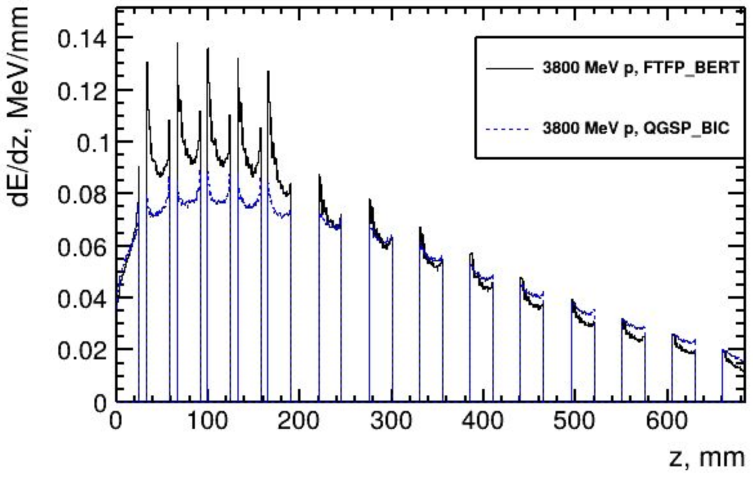


https://www-nds.iaea.org/spallations/

Energy deposition profiles from 3800 MeV protons



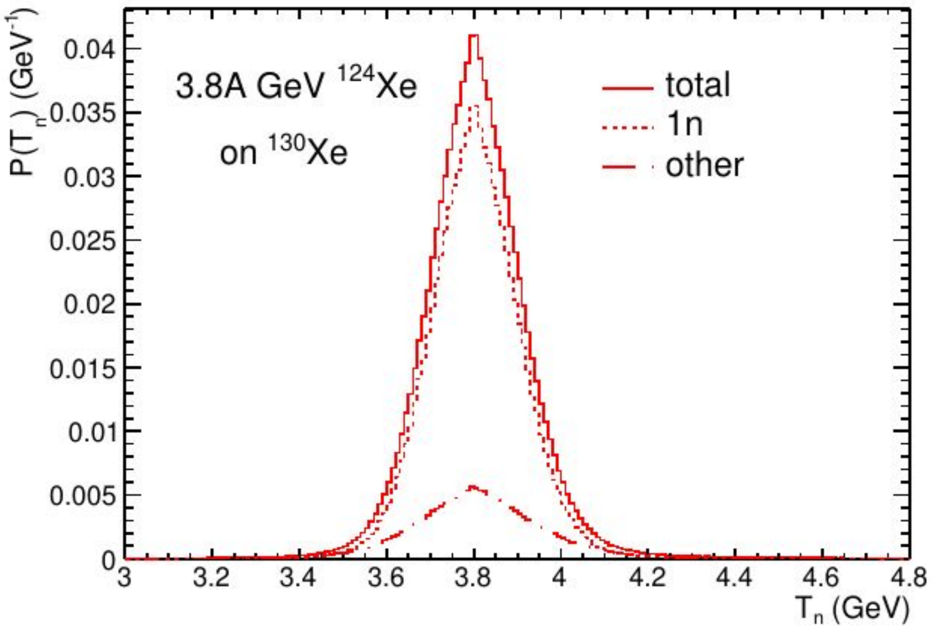
Total



Secondary nuclei

- Same results as for neutrons, but EM processes are more prominent in the energy deposition

Neutrons from EM dissociation in the BM@N experiment



- The Coulomb field of the target nucleus induces the photodisintegration of the Xe^{124} nucleus from the beam. At these energies the channel of a single neutron emission is dominating
- The mean kinetic energy of neutrons is equal to 3.8 GeV. They are emitted in a narrow frontal cone.
- The resulting quasimonoenergetic neutron beam is suitable for the calibration of HGND detector and its prototype.

Pshenichnov, I. A., et al.
Electromagnetic dissociation of nuclei: From LHC to NICA.
International Journal of Modern Physics E (2024): 2441007.