Adam Para, Fermilab
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STUDIES OF HADRON SHOWERS MODELING IN GEANT4 (PEEK UNDER THE HOOD)

Motivation

- Ideally: a robust, trustworthy shower simulation program would be invaluable tool in designing, predicting performance and understanding of calorimeters for High Energy Physics
- We have nearly achieved this objective for electromagnetic calorimeters (EGS4)
- Simulation of hadronic showers/hadron calorimeters is not very reliable, because it involves strong interactions physics (high energy part) and nuclear physics and we do not have solvable complete theory

Attitudes towards GEANT4: Two Extremes

- I understand my detector because GEANT4 reproduces my data
- Simulations are a waste of time and effort because the modeling codes are unreliable and they do not reproduce the results of my/his/her measurement X

- There is no 'GEANT4' simulation. GEANT4 is a tool-box with various physics models
- Every physics model has its area of validity and accuracy. Any specific simulation has its own systematic error which must be evaluated. For example: even EGS4 is not a very precise tool for high energy electrons when deep inelastic scattering contribution becomes significant.

Simulation of Energy Deposition in Hadron Calorimeters

- High energy hadron interacts with nucleus producing (multiplicity, composition and energy distribution of produced particles)
- These characteristics are modified by the nuclear effects.
- Target nucleus undergoes some transformation (spallation, evaporation, nuclear breakup). Large number of neutrons, some protons and nuclear fragments are produced. Some fraction of the kinetic energy of projectile is used to overcome nucleons binding energy.
- Most of the nuclear effects depend on a specific isotopes
- Particles dissipate their energy (continuous or production of low energy delta electrons, which in turn propagate).
- Some particles leave the detector volume (neutrinos, muons,some neutrons)
- Many particles stop and decay
- Some muons are captured
- Many neutrons are captured and relese most of the binding energy in a form of gamma rays

Simulation of Experimental Signals

- Hadronic shower transfers (some) energy to the host medium
- Produced signals (light, ionization, phonons) depend on the details of medium (electrons configuration, band structure, defects)
- Many final particles have sub-milimeter ranges.. Very detailed detector geometry may be of critical importance
- Signals (electrons, photons) propagate through the medium (dissipation, scattering, avalanches…)
- Front end electronics: distortions, pile-up, malfunctions..
- Data analysis: cuts, algorithms..

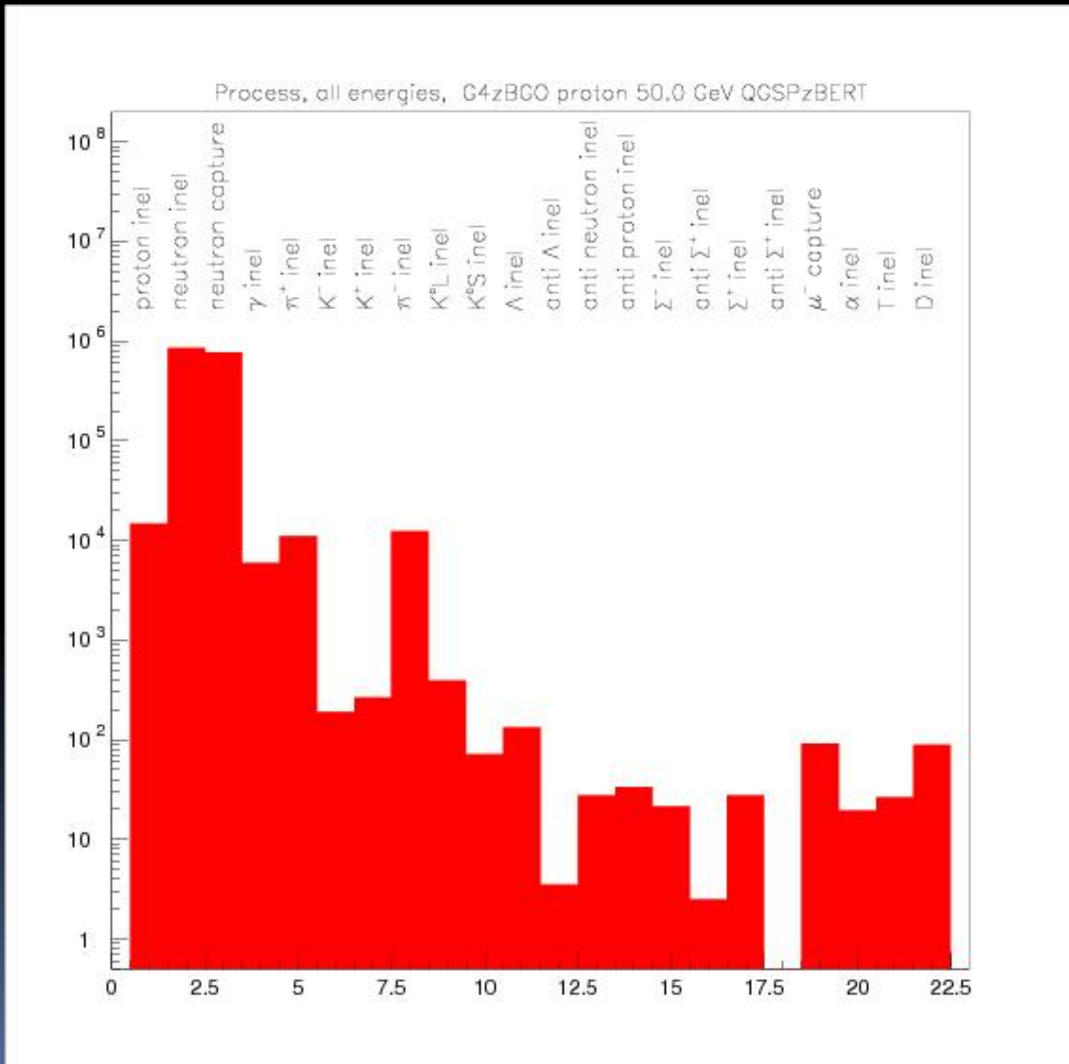
- This is an incomplete list.. If the simulation does not agree with the data: at least one step is incorrect. But which one?
- Tuning: change some parameters soemewhere to make the simulation and data agree. May be sufficient for an effective description, but no predictive power.
- Step-by-step evaluation of the adequacy of the simultion is necessary.

QGSP_BERT Physics list

- QGSP_BERT modeling obeys energy conservation. Other models, in general, do not
- But the use of QGSP_BERT modeling is restricted to low energy interactions (below 10 GeV)

- Will show simulated 50 GeV protons in BGO, 1000 events
- Have other particles (pions, neutrons), other energies, other target materials, other physics lists too
- Thousands of plots (image database – Hans Wenzel)
- This is part of a problem: need a systematic procedure for evaluations/comparisons..
- This is a very rough illustration of the physics content of shower simulation

Long List of Physics Processes Simulated



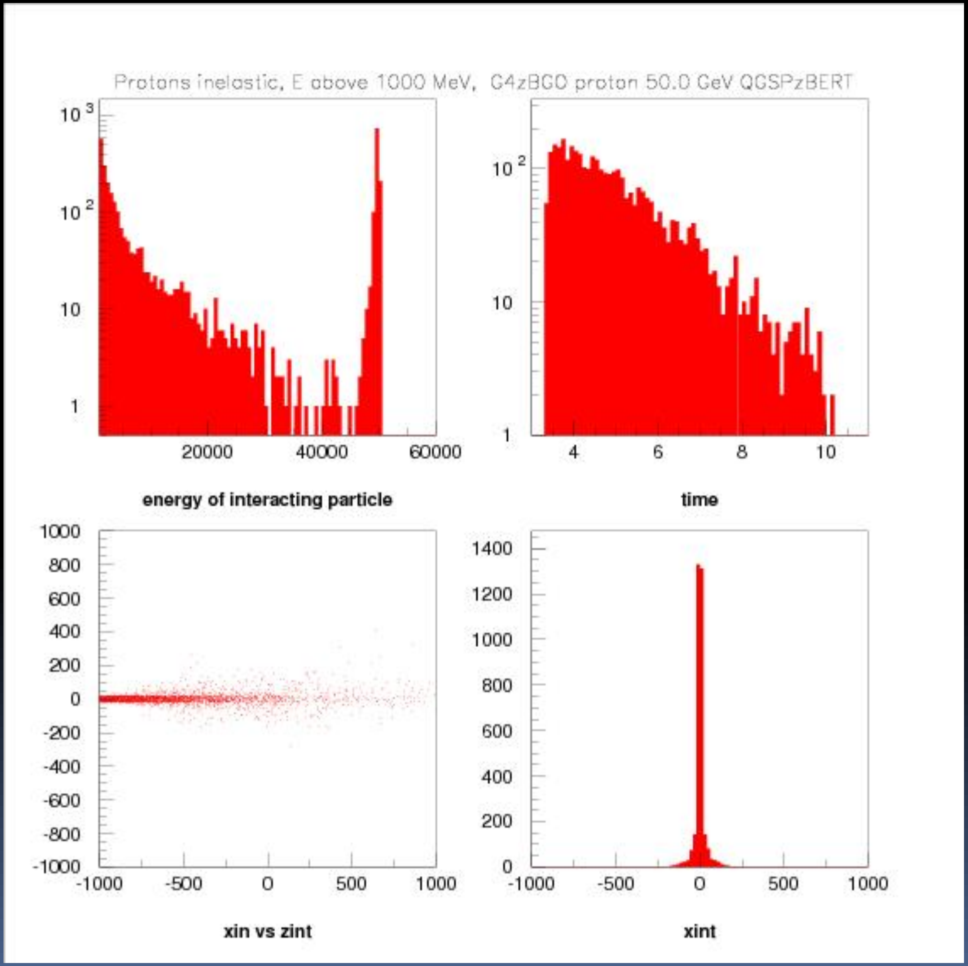
- inelastic collisions of protons (~10 interaction s in 50 GeV shower)
- inelastic collisions of neutrons ~1000
- neutron capture ~800
- inelastic interactions of mesons ~20
- Inelastic interaction of baryons ~0.1
- muon capture ~0.1

Nucleons inside Hadron Showers

- There are several categories of nucleons:
  - Produced in high energy hadron-nucleus (QCD) interaction
  - Spallation nucleons
  - Evaporation nucleons
  - Nucleons produced in fission reactions
- I have arbitrarily divided nucleon interactions into two groups:
  - High energy ($E>1$ GeV)
  - Low energy ($E<100$ MeV)

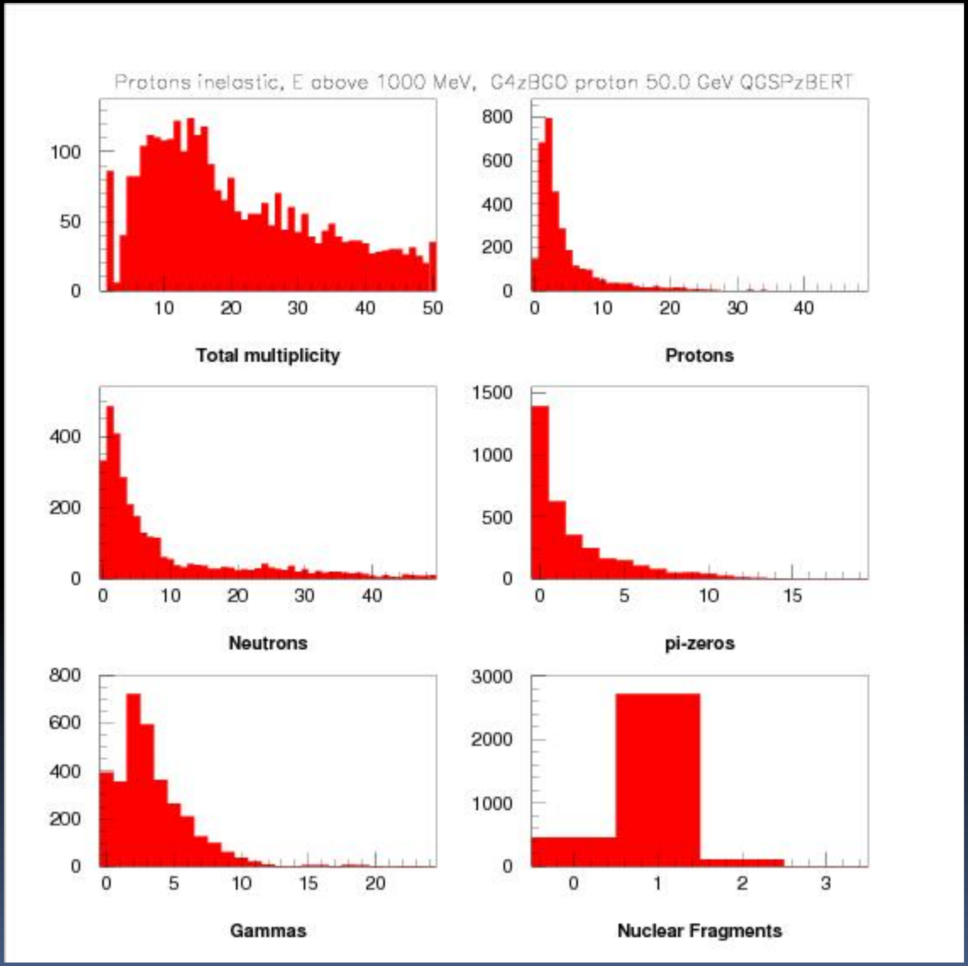
Interactions of High Energy Proton (E>1 GeV)

General Characteristics



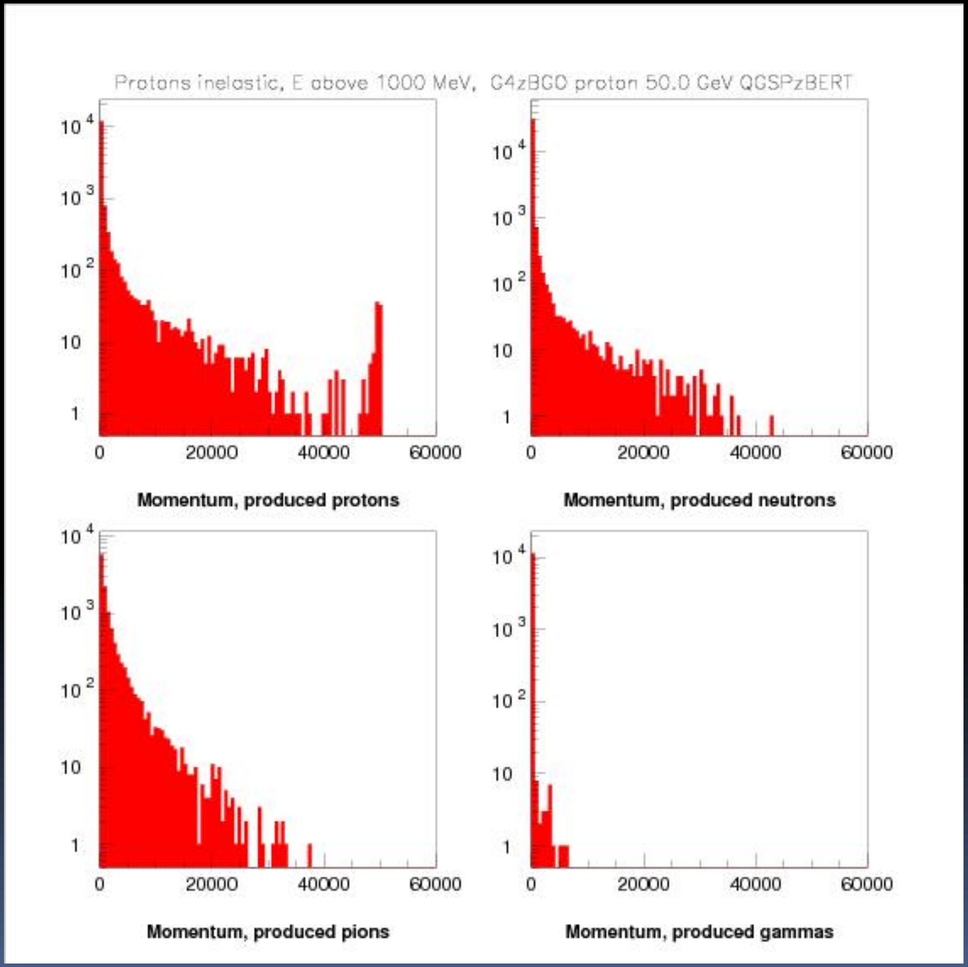
- mix of high (50 GeV) and low (~1 GeV) interactions
- prompt < 10 nsec
- confined to a narrow tube with ~2 cm radius

Multiplicity of Produced Particles



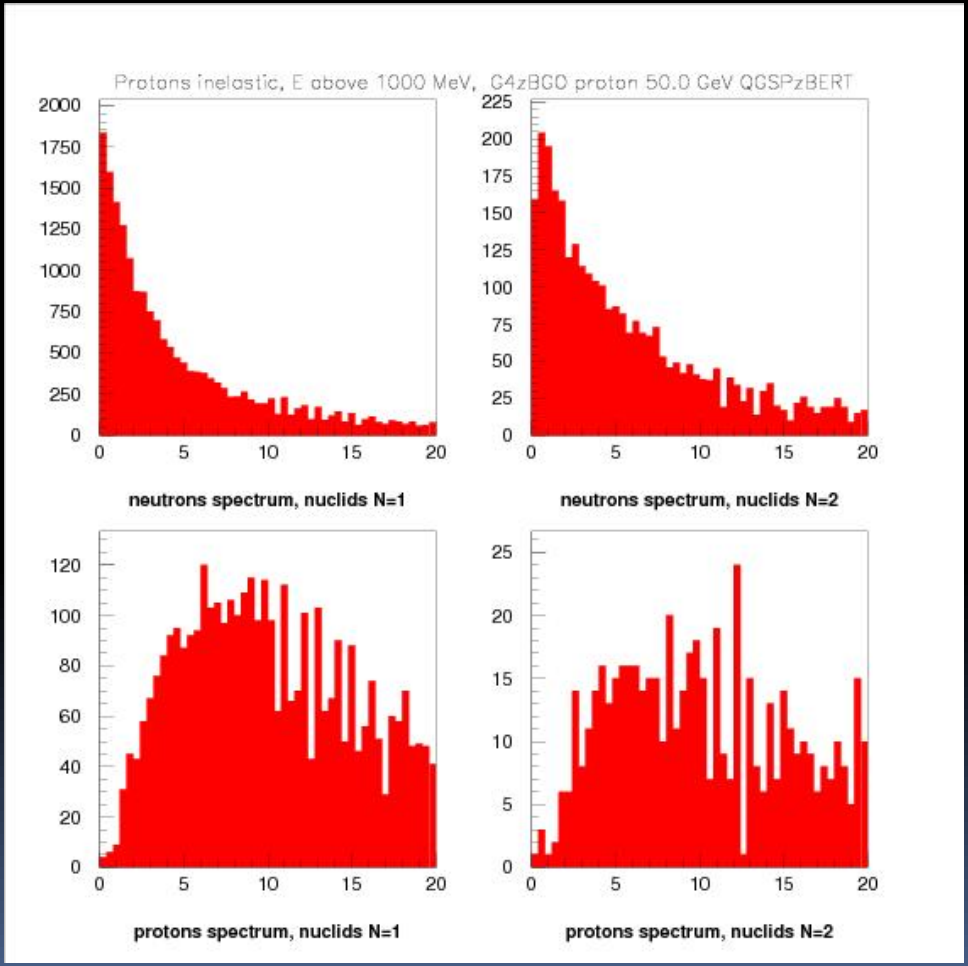
- Broad distribution, very long tail due to neutrons
- most of the time a single nucleus
- some elastic collisions, some events of nuclear breakup

Spectra of Produced Particles



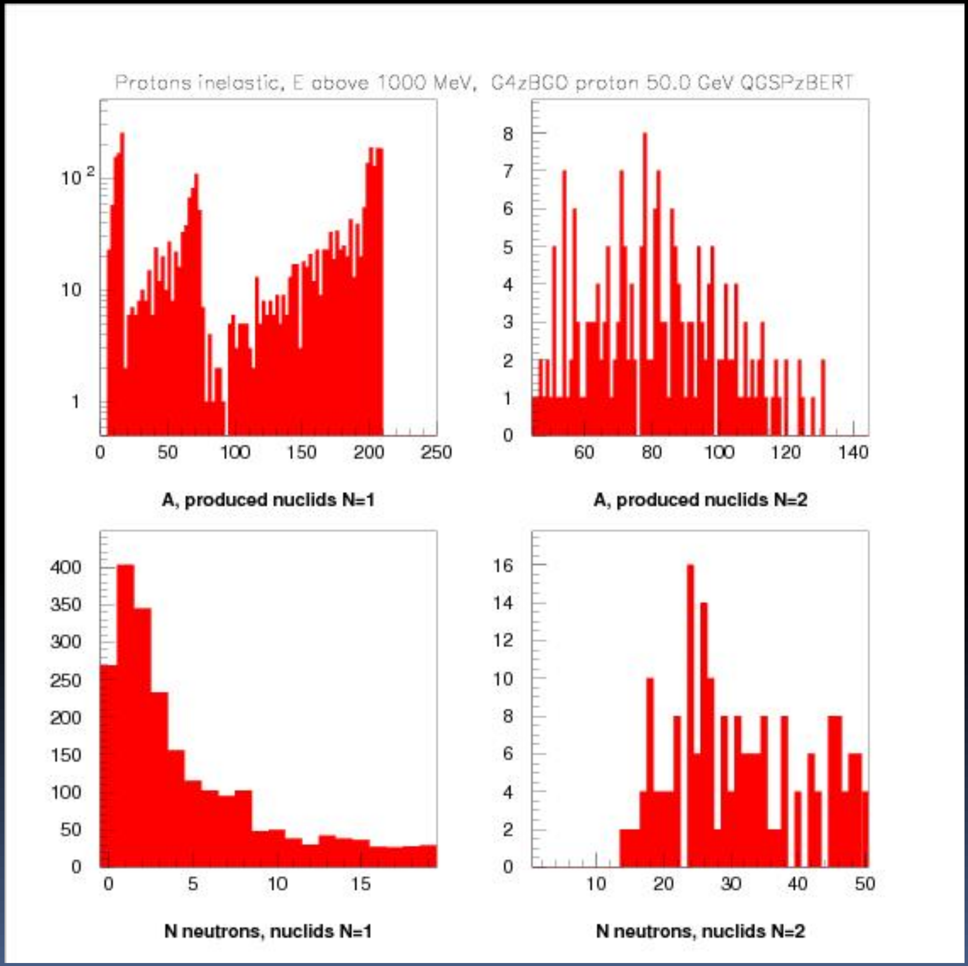
- leading particle effect
- most of hadrons at low energies
- most of protons, neutrons and gammas at very low (~nuclear energies)

'Nuclear Nucleons'



- very low energy neutrons, peaked at zero
- slightly higher energies when the nucleus breaks up
- protons definitely higher energy than neutrons
- <Ep> ~6-7 MeV

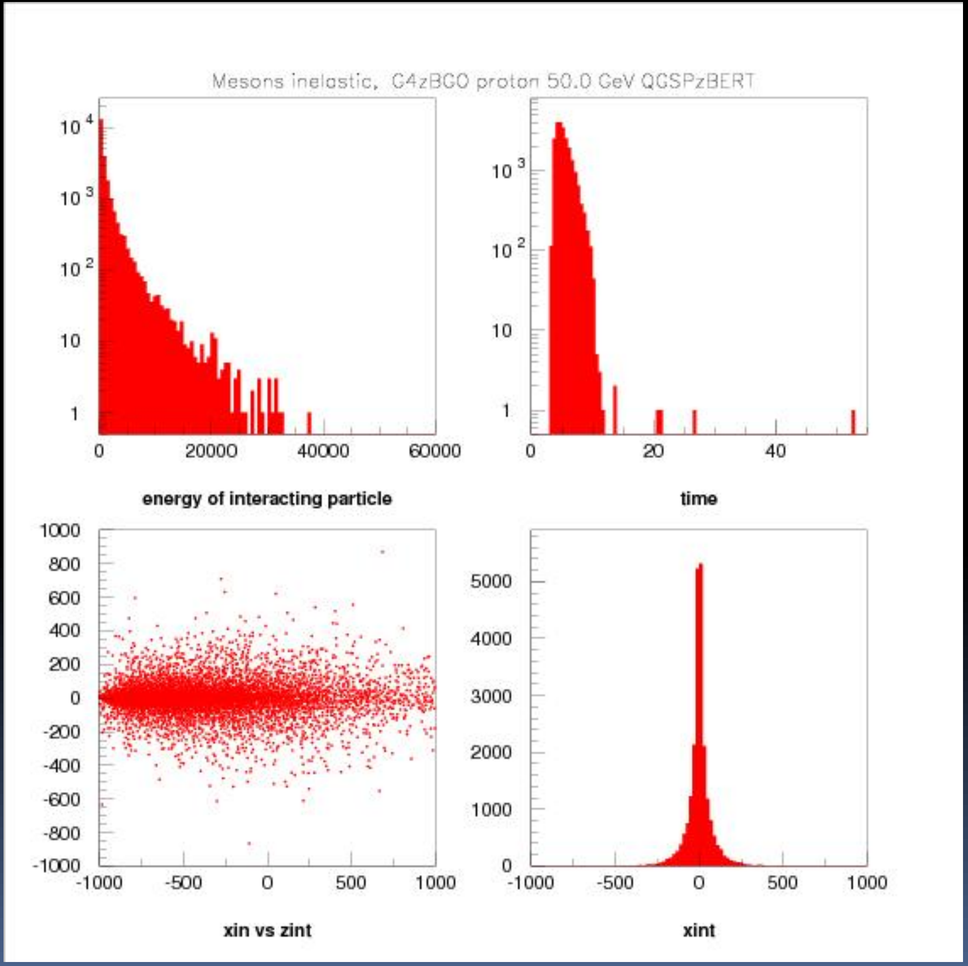
Nuclear Reactions



- Kick out some number of nucleons from a nucleus
- Sometimes break Bi nucleus into two large pieces.
- The latter produces very large number of neutrons

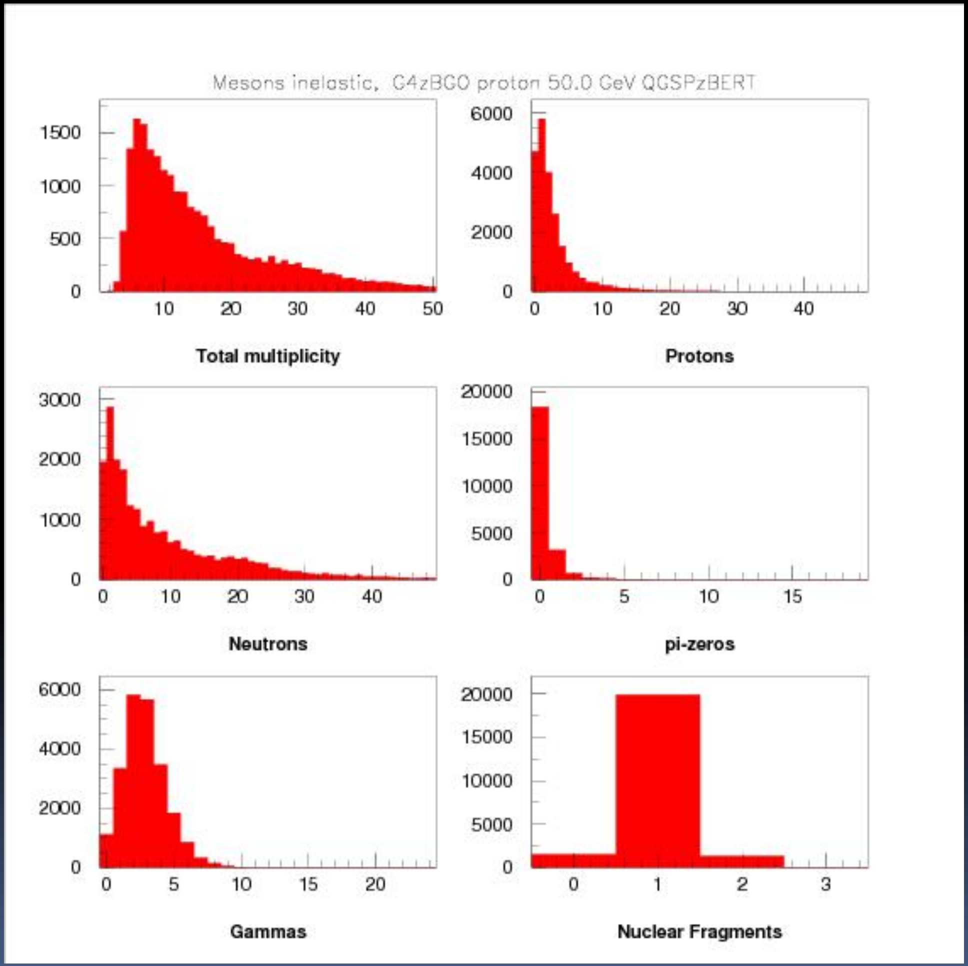
Meson Interactions

General Characteristics



- most of the interactions occur at very low energies
- prompt < 10 nsec
- confined to a narrow tube with ~10 cm radius

Multiplicity of Produced Particles



•Broad distribution, very long tail due to neutrons
• most of the time a single nucleus
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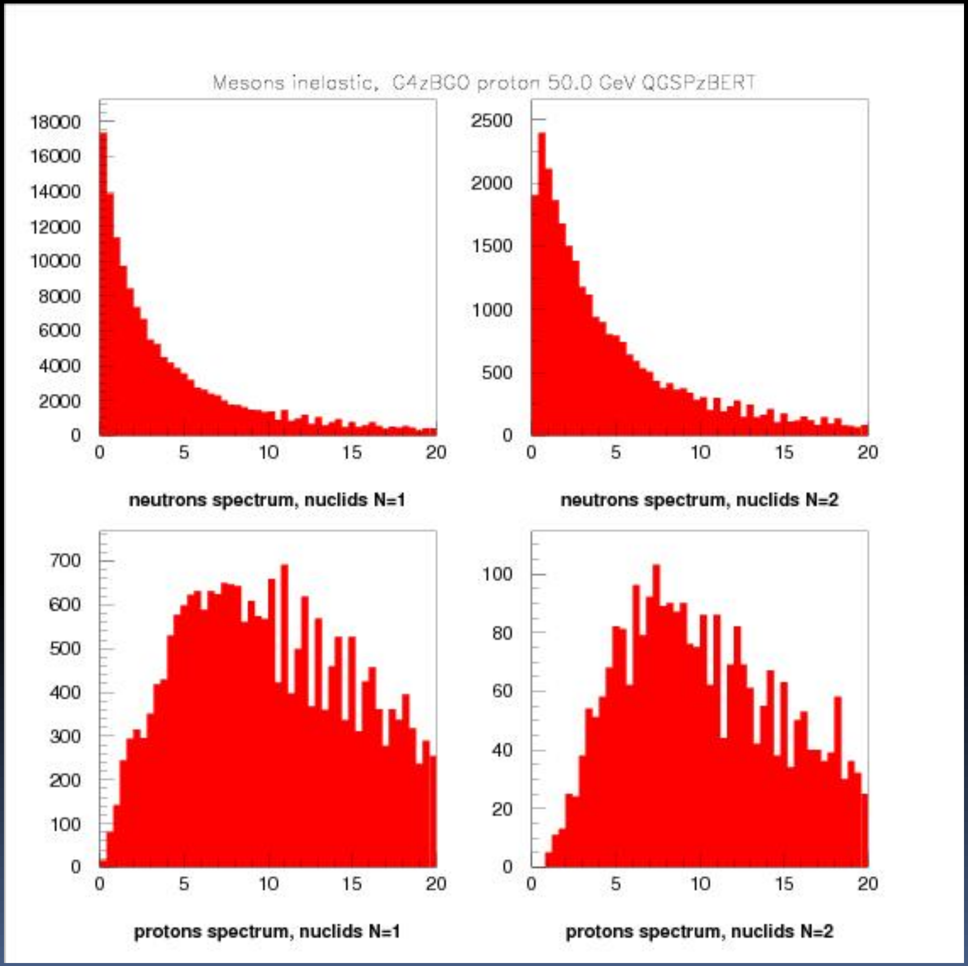
'Nuclear Nucleons'



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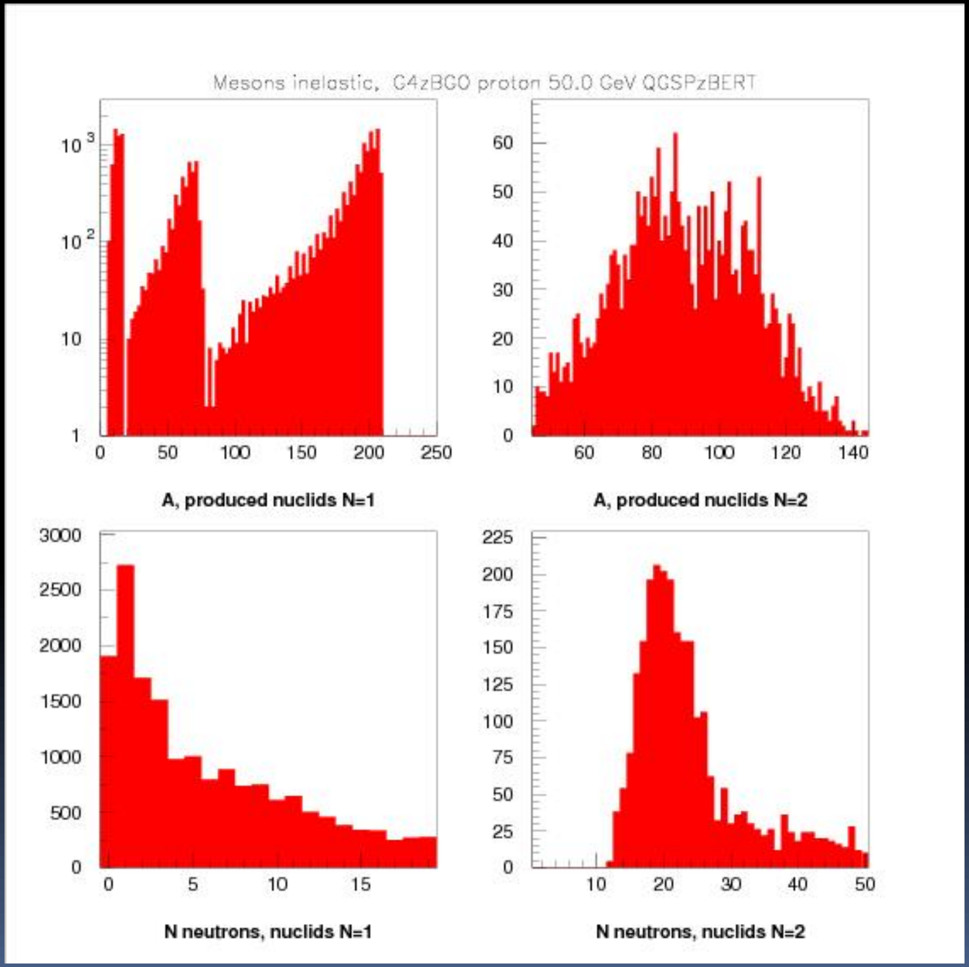

- Kick out some number of nucleons from a nucleus
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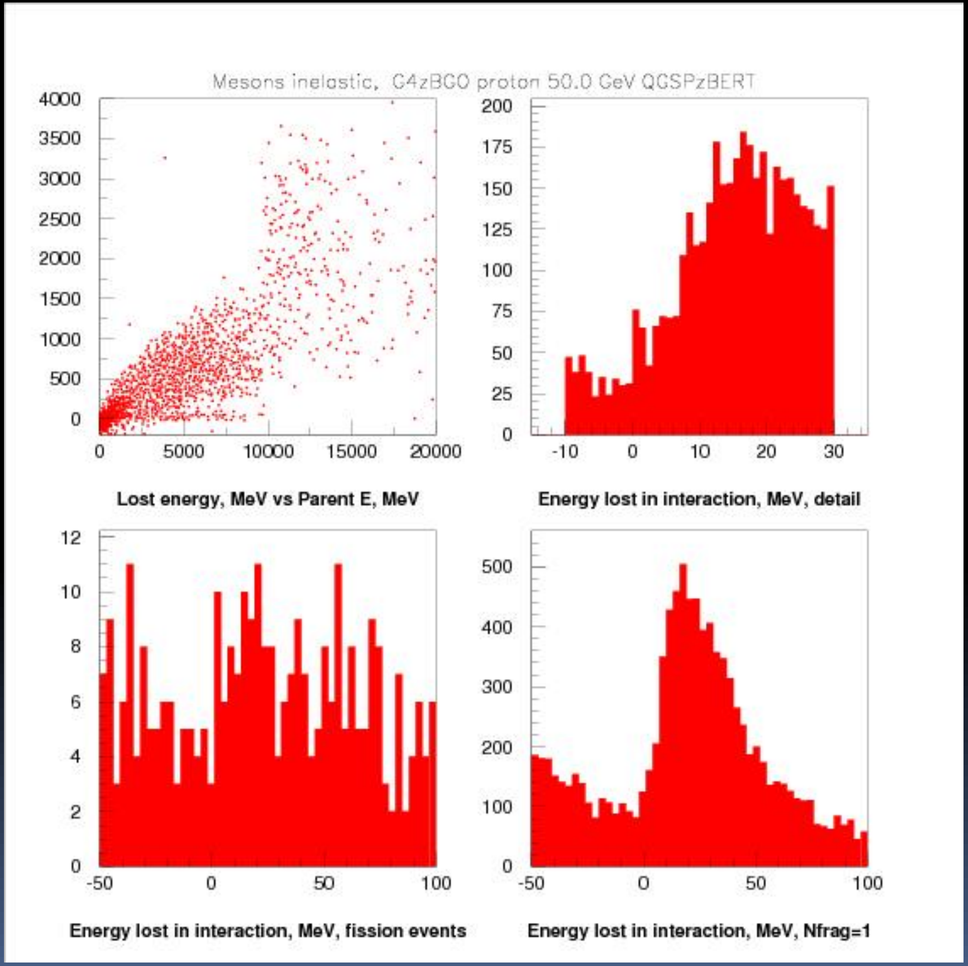
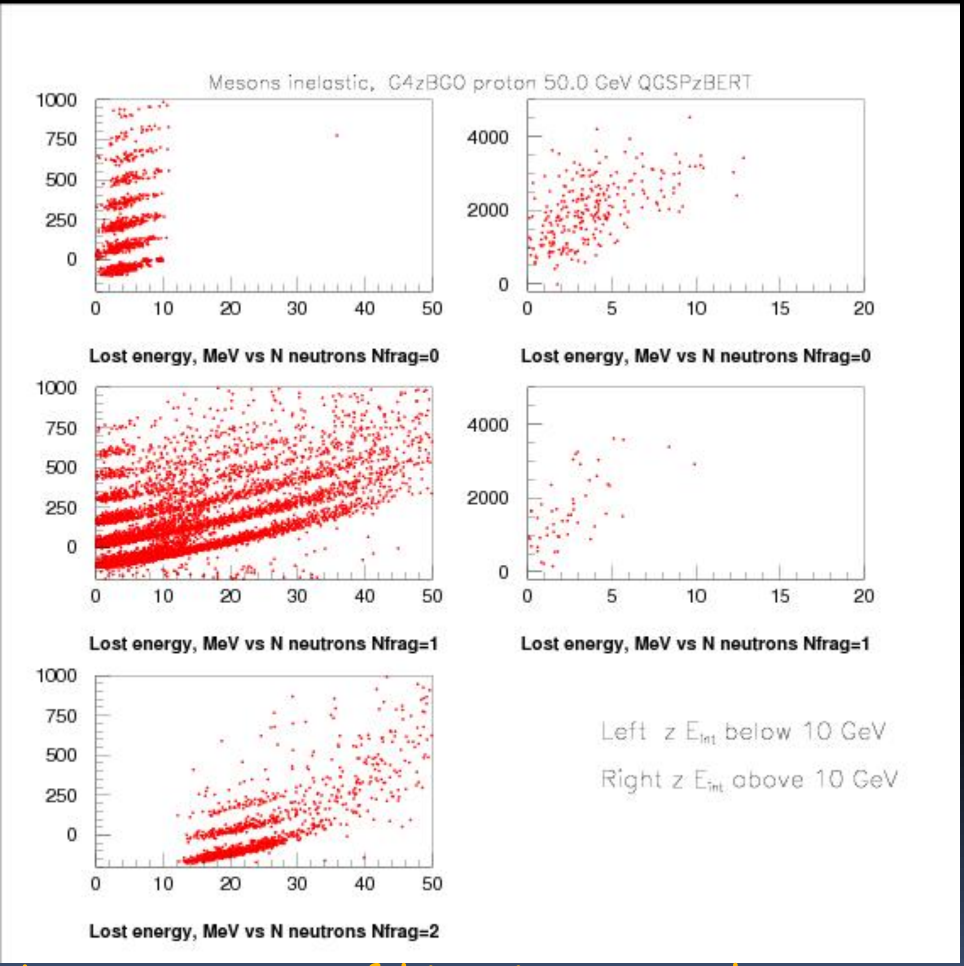
Kinetic Energy (non) Conservation in a Collision

Total kinetic energy, after – before interaction vs energy of the interacting particle



very different modeling of hadron-nucleus interaction below and above 10 GeV

Energy Lost vs Number of Neutrons

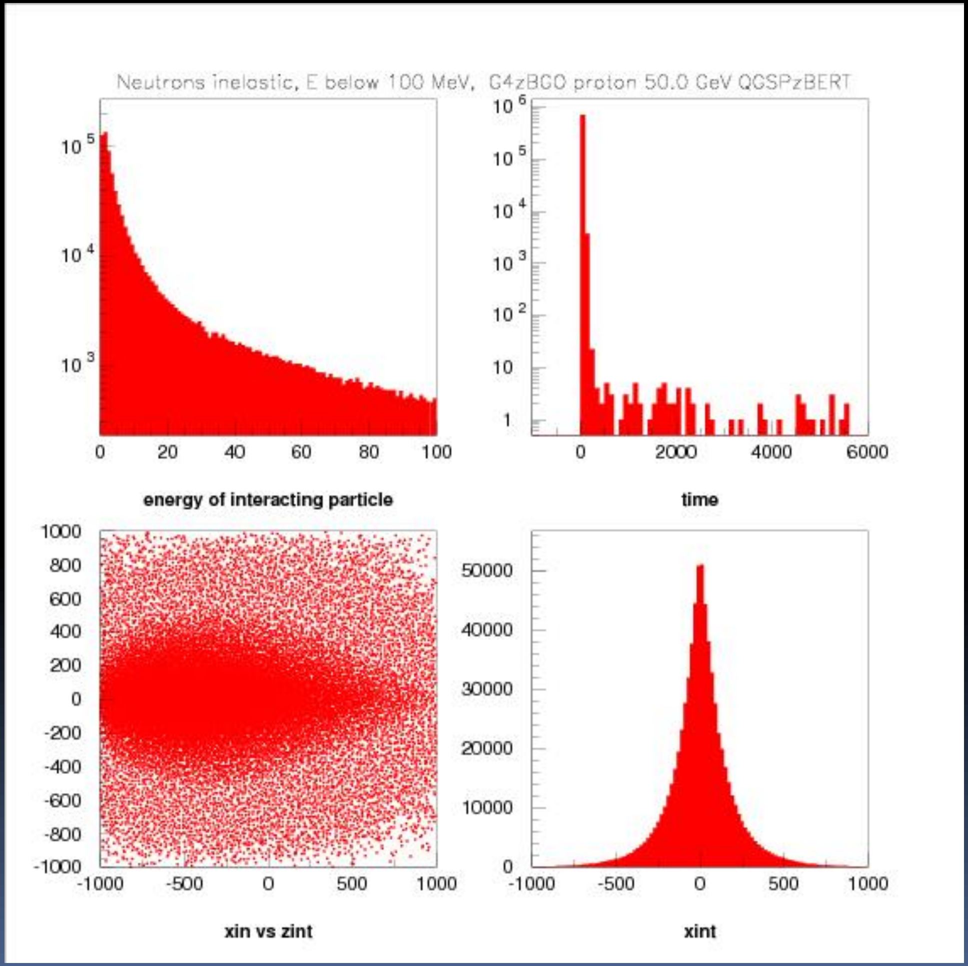


Large amount of kinetic energy lost to produce pions. Fluctuation of charged pion multiplicities contribute to the energy resolution.

- Above 10 GeV: very large missing energy, not consistent with a small number of neutrons. Energy is not conserved
- Below 10 GeV:
  - no nuclear fragments:
    - missing energy increasing with number of neutrons
    - bands reflecting the number of mesons produced
  - one nuclear fragment:
    - large number of neutrons
    - missing energy increasing with number of neutrons
    - bands reflecting the number of mesons produced
  - two nuclear fragments:
    - as above, but somewhat less energy missing (fission!) , more neutrons

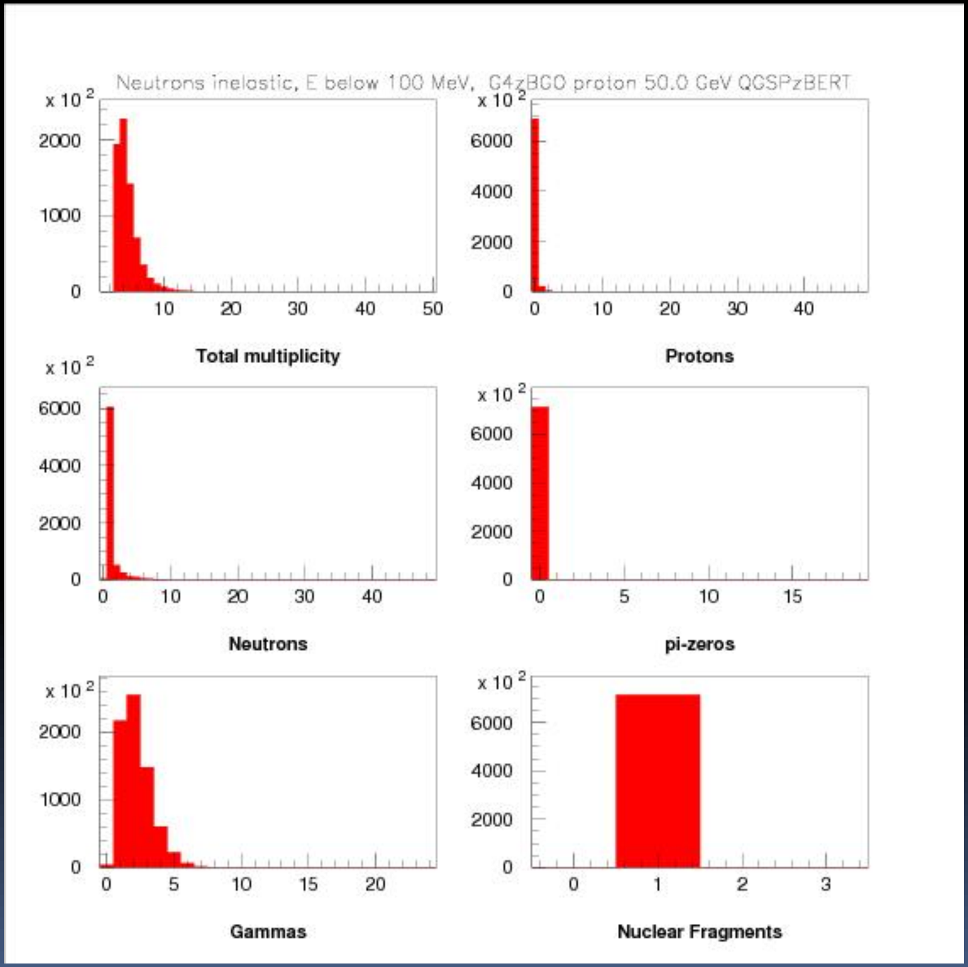
Neutrons, Low Energies (<100 MeV)

General Characteristics



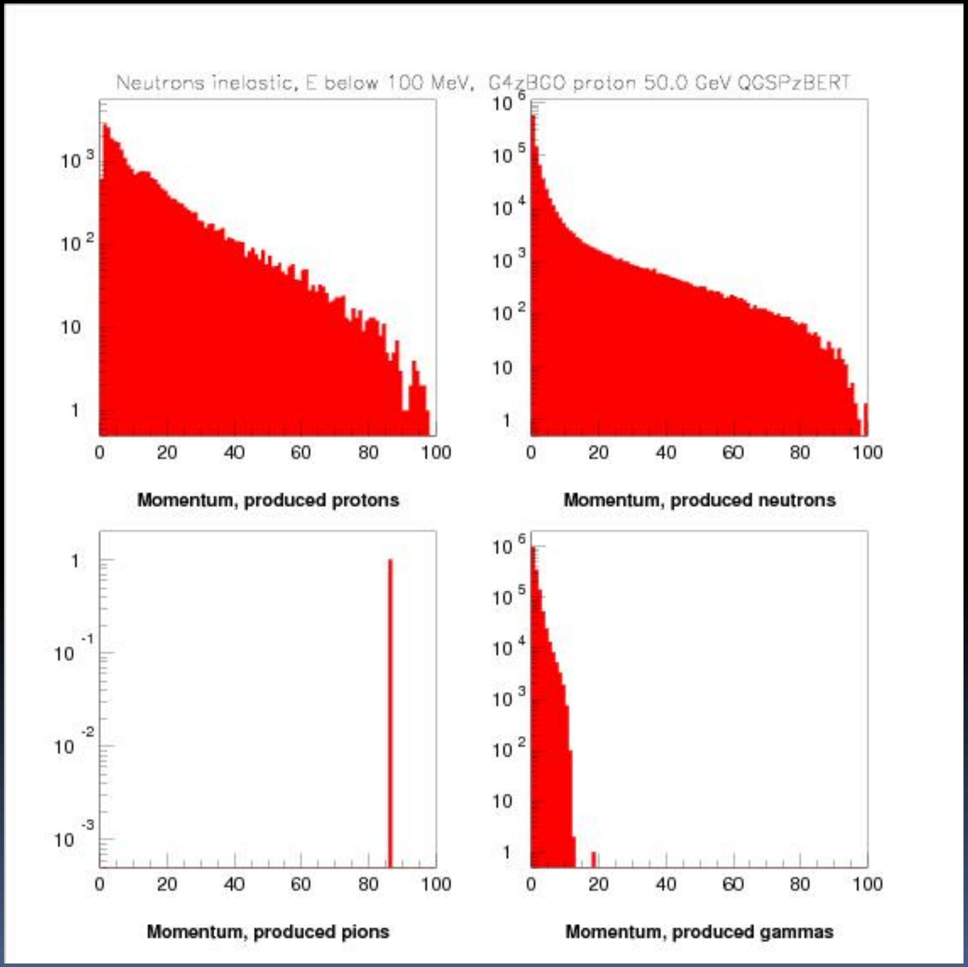
- most of the interactions occur at very low energies
- prompt < 10 nsec
- rather broad tube extending to ~20-30 cm radius

Multiplicity of Produced Particles



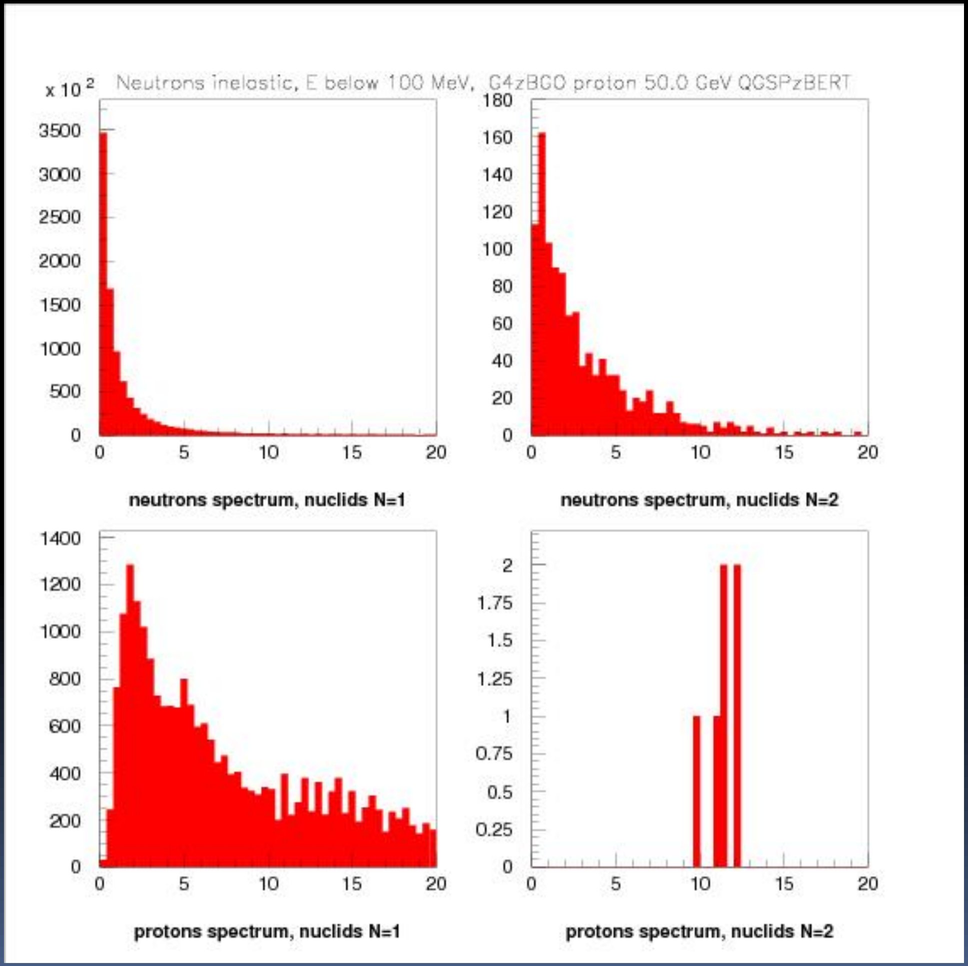
- Mostly gammas
- Narrow distribution,
- most of the time a single nucleus

Spectra of Produced Particles



- Mostly gammas
- very soft nuclones (evaporation)
- one pion produced! (tail of the Fermi motion?)

‘Nuclear Nucleons’



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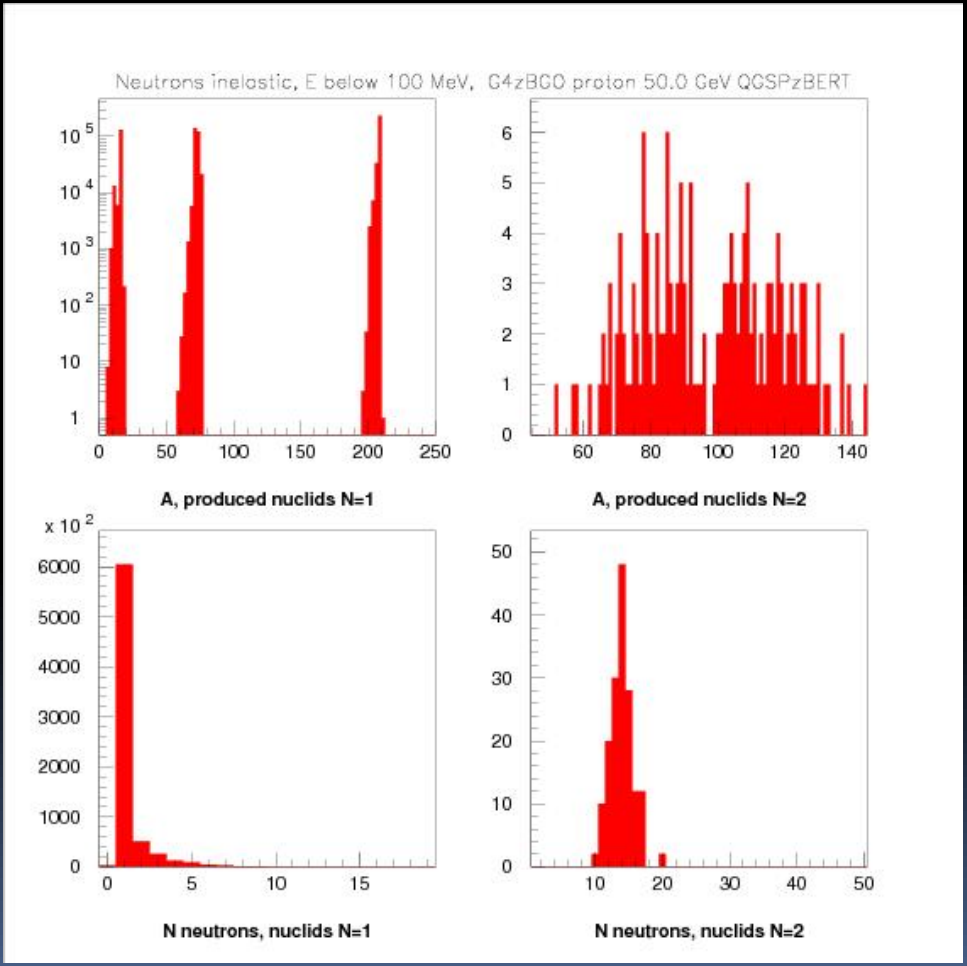
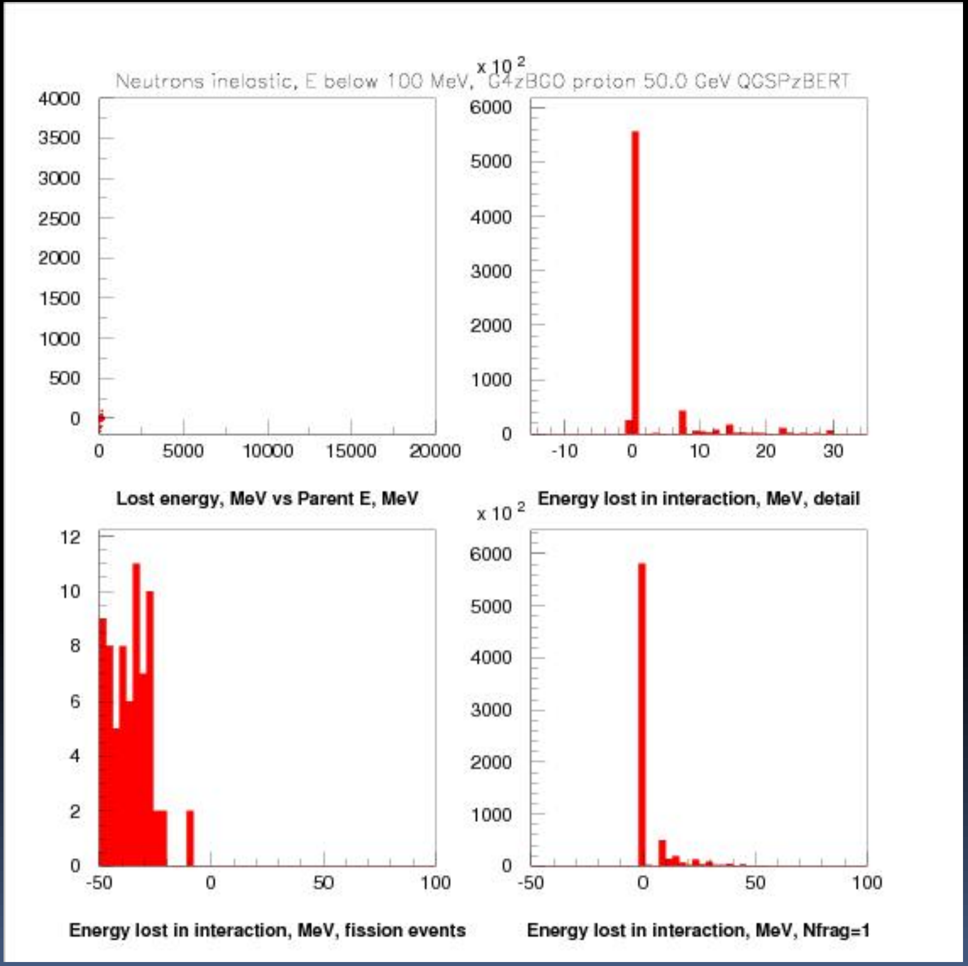
Nuclear Reactions



- Kick out small number of nucleons from a nucleus
- Sometimes break Bi nucleus into two large pieces.
- The latter produces larger number of neutrons

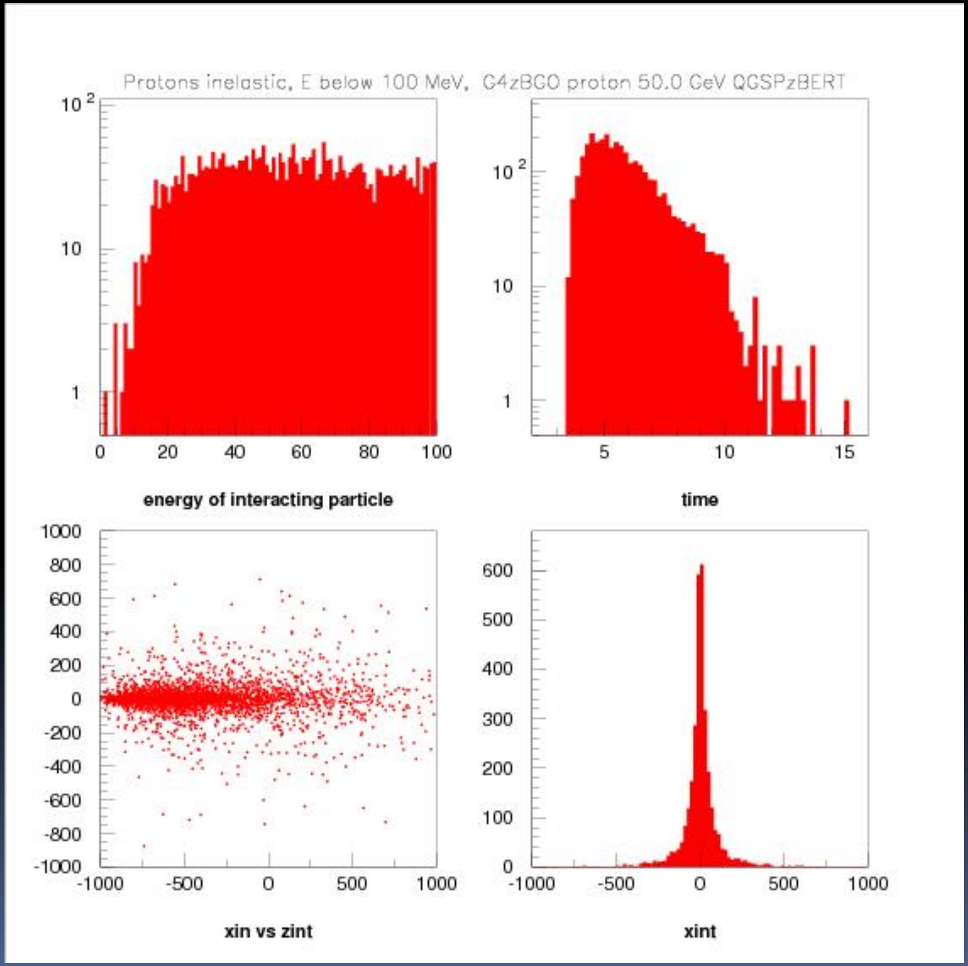
Energy Lost in a Collision



- energy gain in fission events
- discrete lines of energy lost to evaporate nucleons

Proton Interactions, Low Energies (<100 MeV)

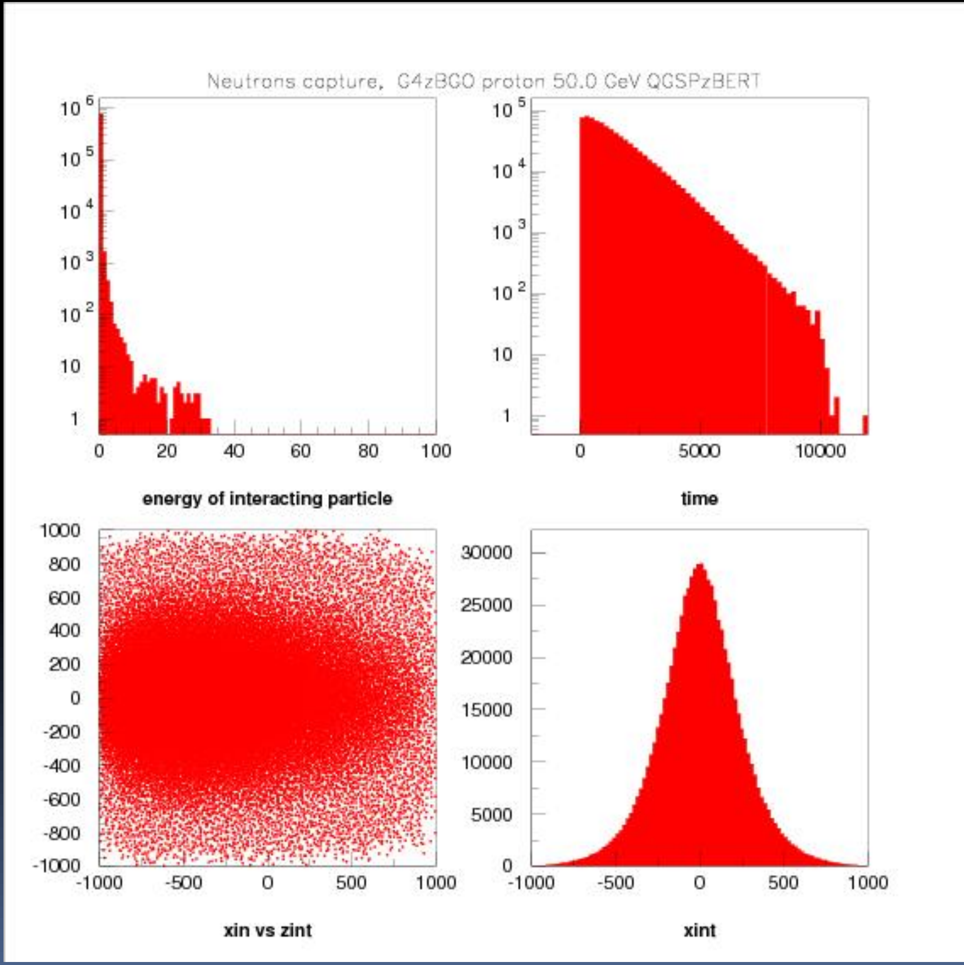
General Characteristics



- most of the interactions occur at very low energies
- Coulomb barrier
- prompt < 10 nsec
- confined to a narrow tube with ~10 cm radius

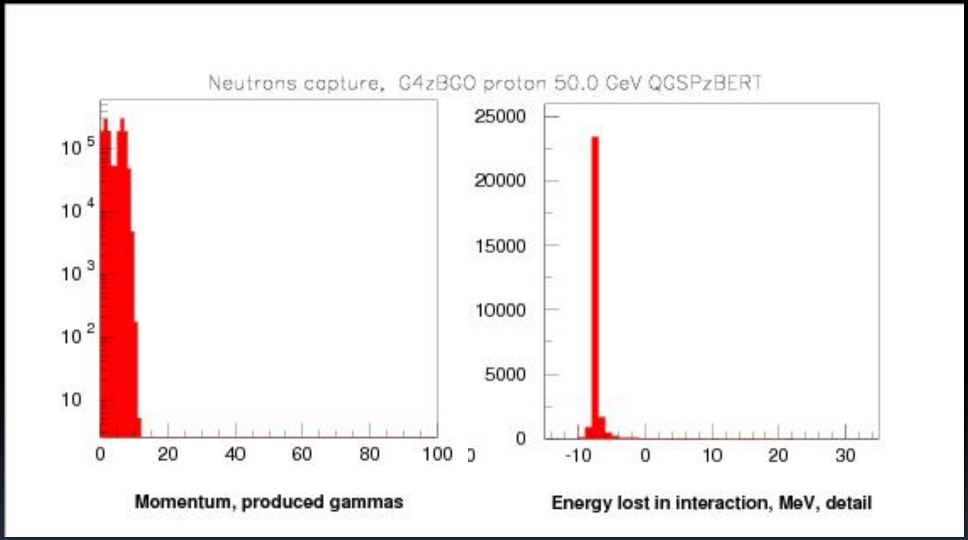
Neutron Capture

General Characteristics



- most of captures occur at low energies< 1 MeV
- ~ 1.5 μsec time constant
- Time constant depends on the material
- extends to large radii ~30-40 cm

Spectra of Produced Particles



- binding energy released as gammas. Effective gain (back) of energy
- Statements about 'nuclear binding energy losses' depend on the medium, integration time and the detector volume
- Detection of capture products (if possible) is much better way to recover the binding energy than detection of kinetic energy via np reaction. Both can be used, naturally..

Not a Summary, because I have shown only a tip of the iceberg

- A lot of physics is included in (at least some of) GEANT simulations
- Simulation of nuclear effects at higher energies inadequate, inducing fluctuations bigger that ones produced by high resolution calorimeters
- Detailed comparison is a huge task, exceeding resources and competence of HEP community, but..
- There are large sectors of human activities which depend on the veracity of simulation far more critically than we do

The Abdus Salam
International Centre for Theoretical Physics

Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

3 - 14 May 2010

Miramare, Trieste, Italy

MAIN TOPICS

- neutron cross section measurements, data reduction and uncertainty estimation
- nuclear reaction theory, nuclear models and codes for cross section calculations
- cross section evaluations using non-model and model fits of experimental data

Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

International Centre for Theoretical Physics

Trieste, Italy

4 – 8 February 2008

244 pages

Prepared by

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Abstract

The International Atomic Energy Agency (IAEA) and the Abdus Salam International Centre for Theoretical Physics (ICTP) organised an expert meeting at the ICTP from 4 to 8 February 2008 to discuss model codes for spallation reactions. These nuclear reactions play an important role in a wide domain of applications ranging from neutron sources for condensed
matter and material studies, transmutation of nuclear waste
astrophysics, simulation of detector set-ups in nuclear and pa
radiation protection near accelerators or in space. The simul
domains use nuclear model codes to compute the production
the particles and nuclei generated in these reactions. These c
implementations of Intra-Nuclear Cascade (INC) or Quantu
models, followed by de-excitation (principally evaporation
discussed in depth the physics contained within the differen
their strengths and weaknesses. Such codes need to be valida
order to determine their accuracy and reliability with resp
Agreement was reached during the course of the worksho
benchmark of the different models developed by different
specifications of the benchmark, including the set of sel
compared to the models, were also defined during the wor
organised under the auspices of the IAEA in 2008, and the firs
next Accelerator Applications Conference (AccApp'09) to be

Benchmark of Nuclear Spallation Models

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Abstract. A summary of the satellite meeting on the Benchmark of Nuclear Spallation Models and an overview of various codes/models participated in this benchmark is presented here.