Hadronic Physics III

Puebla Geant4 Tutorial
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Outline

- String Models
  - quark-gluon string, Fritiof fragmentation
- Chiral Invariant Phase Space (CHIPS) model
- Other models
  - capture
  - fission
  - isotope production
String Models

- For incident \( p, n, \pi, K \)
- Also for high energy \( \gamma \) when CHIPS model is connected
- \(~10\ \text{GeV} < E < \sim\text{TeV}\)

Model handles:
- selection of collision partners
- splitting of nucleons into quarks and diquarks
- formation and excitation of strings
- string hadronization

Damaged nucleus remains. Another Geant4 model must be added for nuclear fragmentation and de-excitation
- pre-compound model, or CHIPS for nuclear fragmentation
String Model Algorithm

- Build up 3-dimensional model of nucleus
- Large $\gamma$-factor collapses nucleus to 2 dimensions
- Calculate impact parameter with all nucleons
- Calculate hadron-nucleon collision probabilities
  - use Gaussian density distributions for hadrons and nucleons
- Sample number of strings exchanged in each collision
- String formation and fragmentation into hadrons
Longitudinal String Fragmentation

- String extends between constituents
- Break string by inserting q-qbar pair according to
  \[ u : d : s : qq = 1 : 1 : 0.27 : 0.1 \]
- At break -> new string + hadron
- Created hadron gets longitudinal momentum from sampling fragmentation functions
- Gaussian \( P_t \), \( \langle P_t^2 \rangle = 0.5 \) GeV
Quark Gluon String Model

- Two or more strings may be stretched between partons within hadrons
  - strings from cut cylindrical Pomerons
- Parton interaction leads to color coupling of valence quarks
  - sea quarks included too
- Partons connected by quark gluon strings, which hadronize
Fritiof Model

Similar to Quark-Gluon string model, except
- no partons are exchanged between projectile and target
- only momentum is exchanged
- has a different set of string fragmentation functions
- valid down to much lower energies (~3 GeV)
Diffraction

- Both QGS and FTF models include diffraction
  - projectile or target or both break up into hadrons
  - amount of diffraction is adjusted empirically
QGSM - Results

$\pi^{-} \text{ Mg} \rightarrow \pi^{+} \ X \ , \ \text{Plab 320 GeV/c}$

Rapidity $\eta = -\frac{1}{2} \ln \left( \frac{E + p_{z}}{E - p_{z}} \right)$

$P_{t}^{2} \ [\text{GeV}^{2}]$
Chiral Invariant Phase Space (CHIPS)

- **Origin:** M.V. Kosov (CERN, ITEP)
- **Use:**
  - capture of negatively charged hadrons at rest
  - anti-baryon nuclear interactions
  - gamma- and lepto-nuclear reactions
  - back end (nuclear fragmentation part) of QGSC model
CHIPS Fundamental Concepts

- **Quasmon**: an ensemble of massless partons uniformly distributed in invariant phase space
  - a 3D bubble of quark-parton plasma
  - can be any excited hadron system or ground state hadron

- **Critical temperature** $T_C$: model parameter which relates the quasmon mass to the number of its partons:
  - $M_Q^2 = 4n(n-1)T_C^2 \Rightarrow M_Q \sim 2nT_C$
  - $T_C = 180 – 200$ MeV

- **Quark fusion hadronization**: two quark-partons may combine to form an on-mass-shell hadron

- **Quark exchange hadronization**: quarks from quasmon and neighbouring nucleon may trade places
CHIPS Applications

- u,d,s quarks treated symmetrically (all massless)
  - model can produce kaons, but s suppression parameter is needed, $\eta$ suppression parameter also required
  - real s-quark mass is taken into account by using masses of strange hadrons
- CHIPS is a universal method for fragmentation of excited nuclei (containing quasmons).
- Unique, initial interactions were developed for:
  - interactions at rest such as $\pi^-$ capture, pbar annihilation
  - gamma- and lepto-nuclear reactions
  - hadron-nuclear interaction in-flight are in progress
- Anti-proton annihilation on p and $\pi^-$ capture at rest in a nucleus illustrate two CHIPS modelling sequences
Modeling Sequence for Proton – antiproton Annihilation (1)
Modeling Sequence for $\pi^-$ Capture at Rest in a Nucleus (1)

- Initially, a nucleon cluster contains a $\pi^-$ particle.
- As the process continues, the quasmon begins to rotate within the nucleon cluster.
- Eventually, the quasmon disappears, and nuclear evaporation begins.
pion captures on a subset or cluster of nucleons
- resulting quasmon has a large mass, many partons
- capture probability is proportional to number of clusters in nucleus
- 3 clusterization parameters determine number of clusters

both quark exchange and quark fusion occurs
- only quarks and diquarks can fuse
- mesons cannot be produced, so quark-anti-quark cannot fuse as in p-pbar case
- because q-qbar fusion is suppressed, quarks in quasmon exchange with neighboring nucleon or cluster
  - produces correlation of final state hadrons
Modeling Sequence for $\pi^-$ Capture at Rest in a Nucleus (3)

- some final state hadrons escape nucleus, others are stopped by Coulomb barrier or by over-barrier reflection
- hadronization continues until quasmon mass reaches lower limit $m_{\text{min}}$
  - in nuclear matter, at this point nuclear evaporation begins
  - if residual nucleus is far from stability, a fast emission of $p$, $n$, $\alpha$ is made to avoid short-lived isotopes
Validation of CHIPS Model for Pion Capture at Rest on Tantalum
Capture Processes

- At rest capture on nuclei
  - G4MuonMinusCaptureAtRest
  - G4PionMinusAbsorptionAtRest
  - G4KaonMinusAbsorption
  - G4AntiProtonAnnihilationAtRest
  - G4AntiNeutronAnnihilationAtRest

- In flight
  - G4HadronCaptureProcess uses following models:
    - G4LCapture (mainly for neutrons)
    - G4NeutronHPCapture (specifically for neutrons)
Fission Processes

- G4HadronFissionProcess can use three models:
  - G4LFission (mostly for neutrons)
  - G4NeutronHPFission (specifically for neutrons)
  - G4ParaFissionModel

- New spontaneous fission model from LLNL
  - available soon
Isotope Production

- Useful for activation studies
- Covers primary neutron energies from 100 MeV down to thermal
- Can be run parasitically with other models
- G4NeutronIsotopeProduction is currently available
  - G4ProtonIsotopeProduction not yet completed
- To use:
  - G4NeutronInelasticProcess nprocess;
  - G4NeutronIsotopeProduction nmodel;
  - nprocess.RegisterIsotopeProductionModel(&nmodel);
- Remember to set environment variable to point to G4NDL (Geant4 neutron data library)
Two string models (QGS, FTF) are provided for high energy (>20 GeV) interactions.

The Chiral Invariant Phase Space model is available for:
- capture at rest
- anti-baryon annihilation
- gamma and lepto-nuclear interactions
- nuclear de-excitation

Other models/processes available include:
- capture at rest and in flight
- fission
- neutron-induced isotope production