Transport Theoretical Studies of Hadron Attenuation in Nuclear DIS

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elementary eN reaction

Motivation

reaction products hadronize long before they reach the detector

estimation of formation time via hadronic radius \((r_h = 0.5 - 0.8 \text{ fm})\)

\[
\tau_f \geq \frac{r_h}{c}
\]

time dilatation: \(t_f = \gamma \tau_f\)
eA reactions at HERMES
  - interactions with (cold) nuclear medium during $t_f$

  space-time picture of hadronization & prehadronic interactions

lessons for more complex heavy-ion collisions
  - jet suppression at RHIC
    - partonic energy loss in QGP
    - (pre-)hadronic FSI

  talk by K. Gallmeister
\[\gamma A, eA \text{ reaction split into 2 parts:}\]

- \[\gamma^*N \rightarrow X\] using PYTHIA & FRITIOF
  - additional consideration of
    - binding energies
    - Fermi motion
    - Pauli blocking
    - coherence length effects

- propagation of final state \(X\) within
  BUU transport model
  - consideration of
    - elastic and inelastic scattering (coupled channels)
hadronic structure of the photon & event classes

\[ |\gamma^*\rangle = \text{DIS} + V + q \bar{q} \]

- **direct** photon interactions:
  - DIS
  - QCD Compton
  - photon-gluon fusion

- **resolved** photon interactions:
  - diffractive VMD
  - VMD
  - GVMD
hadronic structure of the photon

\[ |\gamma^*\rangle = V + q + q \]

\[ \sigma_i / \sigma_{\text{tot}} (\gamma^*N) \]

\[ W = 5 \text{ GeV} \]

\[ Q^2 \text{ [GeV}^2\text{]} \]

\[ Q^2 \text{ [GeV}^2\text{]} \]

- VMD
- GVMD
- direct
shadowing of the vector meson component

- coherence length:
  distance that $\gamma^*$ travels as a vector meson fluctuation

- coherence length $>$ mean free path inside nucleus

- density of nucleons participating in the production process reduced

- influences reactions triggered by the vector meson component (e.g. $\gamma^* N \rightarrow \rho^0 N$)

\[
l_{V} = \frac{1}{|k_{V} - k_{\gamma}|} \approx \frac{2\nu}{Q^2 + m^2_{V}}
\]
hard interactions (e.g. direct $\gamma^* N$ reaction)
- excitation of hadronic strings
- fragmentation according to the Lund model

\[ \text{production point of color neutral prehadron} \]
general approach in transport model

- string fragments very fast into color-neutral prehadrons \( t_p = 0 \)
- prehadrons need formation time \( t_f = \gamma_h \tau_f \) to build up hadronic wave function
- prehadronic cross section \( \sigma^* \)
determined by constituent quark model

\[
\sigma_b^* = \frac{\#q_{\text{orig}}}{3} \sigma_b \\
\sigma_m^* = \frac{\#q_{\text{orig}}}{2} \sigma_m
\]

HERMES kinematics

- \( \rho \)
- \( \phi \)
- \( \pi^0 \)
- \( K^+ \)
- \( K^- \)
effective cross section of nucleon debris

\[ \nu = 25 \text{ GeV} \]
\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \sigma_{\text{eff}} \text{ [mb]} \]
\[ t [\text{fm/c}] \]

comparison with

gluon bremsstrahlung model

C. Ciofi degli Atti and B. Z. Kopeliovich,

starting time of (pre-)hadronic FSI

Comparison with Lund estimate

A. Bialas and M. Gyulassy, NPB 291 (1987) 793

\begin{align*}
\langle t_{FSI} \rangle &\leq \langle t_f \rangle \\
\langle t_f \rangle &\leq \langle t_p \rangle
\end{align*}
DIS of complex nuclei

- “leading” prehadrons (= target-, beam remnants) can undergo FSI directly after $\gamma^*N$ interaction

- hadrons that solely contain quarks from string fragmentation start to interact after $\tau_f$

FSI

- production of new particles
- redistribution of energy
BUU transport model

- for each particle species $i$ ($i = N, R, Y, \pi, \rho, K, \ldots$)

exists a Boltzmann-Uehling-Uhlenbeck equation:

$$
\left( \frac{\partial}{\partial t} + (\nabla_{\vec{p}}H) \nabla_{\vec{r}} - (\nabla_{\vec{r}}H) \nabla_{\vec{p}} \right) f_i(\vec{r}, \vec{p}, t) = I_{\text{coll}} [f_1, \ldots, f_i, \ldots, f_M]
$$

$f_i$: phase space density

$H$: Hamilton function

$$H = \sqrt{(\mu + U_s)^2 + \vec{p}^2}$$

- set of BUU equations coupled via $I_{\text{coll}}$ and mean field

products of $\gamma^*A$ reaction need not be created in primary $\gamma^*N$ reaction
Results

HERMES:

- look for CT in incoherent $\rho^0$ electroproduction off $^{14}\text{N}$
  \[ \nu \approx 10 - 20 \text{GeV}, \quad Q^2 \approx 0.5 - 5 \text{GeV}^2 \]

- diffractive $V$ production: $\gamma^* N \rightarrow \rho^0 N$

- size of initially produced $q\bar{q}$ pair is expected to decrease with increasing $Q^2$
  - early stage of evolution:
    small $q\bar{q}$ pair interacts mainly via its color dipole moment:
    \[ \sigma_{q\bar{q}} \sim \text{diameter}^2 \]

- large energies:
  - $q\bar{q}$ frozen in small sized configuration while passing nucleus

\[ T_A = \frac{\sigma_{\gamma^* A \rightarrow \rho^0 A^*}}{A \sigma_{\gamma^* p \rightarrow \rho^0 p}} \]

effects nuclear transparency ratio:
Comparison with Hydrogen data

- experimental $t$-cut: $|t| > 0.09$ GeV$^2$
  - to get rid of coherent $\rho^0$ production: $\gamma^* A \rightarrow \rho^0 A$
BUU & Glauber theory agree with experiment

No CT in both calculations
Only coherence length effects
hadron attenuation in DIS off nuclei

- multiplicity ratio:
  \[ R_M^h(z_h, p_T, \nu) = \left( \frac{N_h(z_h, p_T, \nu)}{N_e(\nu)} \right) A \left( \frac{N_h(z_h, p_T, \nu)}{N_e(\nu)} \right) D \]
  \[ z_h = \frac{E_h}{\nu} \]

- Experiments:
  - EMC: 100-200 GeV \( \mu \)-beam on \(^{64}\)Cu
  - HERMES: 27.6 GeV e\(^+\)-beam on \(^{14}\)N, \(^{20}\)Ne, \(^{84}\)Kr
  - Jefferson Lab: 5.4 GeV e\(^-\)-beam on \(^{12}\)C, \(^{56}\)Fe, \(^{208}\)Pb

- attenuation due to
  - partonic energy loss
    (X.N. Wang et al., F. Arleo)
  - (pre)hadronic absorption
    (A. Accardi et al.) + rescaling of fragmentation function
    (B. Kopeliovich et al., T. Falter et al.)
**DIS off proton**

- **HERMES** \( \nu = 2.5 - 24 \text{ GeV}, \quad Q^2 > 1 \text{ GeV}^2, \quad W > 2 \text{ GeV} \)
- **red curves**: calculation w/o cuts on hadron kinematics and assuming 4\(\pi\)-detector

![Graph showing hadron production rates](chart.png)
charged hadron production in DIS off $^{84}$Kr at HERMES

- including all experimental cuts
- accounting for angular acceptance of HERMES detector

- average kinematic variables from simulation:
multiplicity ratio of charged hadrons

- w/o prehadronic FSI

prehadronic interactions needed
charged hadrons

– with prehadronic interactions

\[ R_{MN} \]

\[ \tau_f > 0.5 \text{ fm/c compatible with } pA \text{ data at AGS energies} \]
- influence of detector geometry ($\tau_f = 0.5$ fm/c)

- needs to be accounted for at $z_h < 0.4$
- important for integrated spectra
$p_T$-spectrum of charged hadrons ($\tau_f = 0.5$ fm/c)

- strong increase at high $p_T > 1$ GeV

- from calculations: $<k_T>_A = <k_T>_N$, i.e. not Cronin!
attenuation of identified hadrons ($\tau_f = 0.5$ fm/c)
double-hadron attenuation ($\tau_f = 0.5$ fm/c)

- leading hadron
  
  $z_1 > 0.5$

- subleading hadron
  
  $z_2 < z_1$

$$R_2(z_2) = \frac{\left(\frac{N_2(z_2)}{N_1}\right)_A}{\left(\frac{N_2(z_2)}{N_1}\right)_D}$$
HERMES @ 12 GeV ($\tau_f = 0.5$ fm/c)

- model also works at lower energies
Jefferson Lab ($\tau_f = 0.5$ fm/c)

- **CLAS detector**
  - larger geometrical acceptance
  - detects more secondary particles from FSI

- **CEBAF**
  - lower energy
  - strong effect of Fermi-motion
model for $\gamma$ and $e$ induced reactions at GeV energies

- combines:
  - qm coherence in entrance channel
  - sophisticated event generation
  - coupled channel transport description of FSI

- can describe
  - coherence length effects in exclusive $\rho^0$ production
  - most features observed in hadron attenuation

- works also for:
  - $\gamma$ and $e$ reactions in resonance region
  - $\pi A$, $p A$ and $A A$ reactions

at HERMES energies

same parameter set

future plans:

- consistent event generation AND space-time picture by PYTHIA
- analysis of future JLab experiments, ultra-peripheral HIC