Electroproduction of hadrons in nuclei

Nicola Bianchi
Bianchi@lnf.infn.it

- Fragmentation Function modifications in the nuclear medium
- HERMES recent and new results
- Expectations from CLAS
- Interpretations

Workshop on In-Medium Hadron Physics, Giessen, 11-13 November 2004
DF on Nucleon & Nuclear Medium

\[ d\sigma^h(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^h(z) \]

Inclusive DIS on nuclei: EMC effect

Medium modifications of Distribution Functions: interpretation at both hadronic (nucleon’s binding, Fermi motion, pions) and partonic levels (rescaling, multi-quark system)
Fragmentation Functions on Nucleon

\[ d\sigma^h(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D^h_f(z) \]

FFs are measured with precision in e+e-
FFs follow pQCD Q^2-evolution like DFs
FFs scale with \( z = E_h/\nu \) like DFs with \( x \)
FFs probabilistic interpretation like DFs

SIDIS multiplicities are also good measurements of FFs:

\[
\frac{1}{N_{DIS}} \frac{dN^h(x, z)}{dz} = \frac{\sum_f e^2_f q_f(x) D^h_f(z)}{\sum_f e^2_f q_f(x)}
\]
SIDIS multiplicities on Nucleon


What happens in a nuclear medium?
Nuclear Attenuation

Observation: reduction of multiplicity of fast hadrons due to both hard partonic and soft hadron interaction.

Production and Formation Times + FF modifications are crucial for the understanding of the space-time evolution of the hadron formation process.
Hadron multiplicity ratio

Experimental observable: hadron multiplicity ratio in nuclei and deuterium

\[
R_M(z, \nu) = \frac{N_h(z, \nu)}{N_{DIS}} = \frac{1}{\sigma_{DIS}} \frac{d^2\sigma_h}{dzd\nu} = \frac{\Sigma e_f^2 q_f(x) D_f^h(z)}{\Sigma e_f^2 q_f(x)}
\]

Determine \( R_M \) versus:

**Leptonic variables:** \( \nu \) (or \( x \)) and \( Q^2 \)

**Hadronic variables:** \( z \) and \( P_t^2 \)

**Different nuclei:** size and density

**Different hadrons:** flavors and mixing of FFs
Experiments

SLAC: 20 GeV e⁻-beam on Be, C, Cu Sn  
PRL 40 (1978) 1624

EMC: 100-200 GeV μ-beam on Cu  

WA21/59: 4-64 GeV ν(ν)-beam on Ne  

HERMES: 27.6 or 12 GeV e⁺-beam on He, N, Ne, Kr, Xe.  
http://www-hermes.desy.de/notes/pub/trans-public-subject.html#HADRON-ATTENUATION

CLAS: 5.4 GeV e⁻-beam on C, Fe, Pb  
E-02-104
The energy range (ν 3-25 GeV) is well suited to study medium effects.

Measurements over the full z range

Possibility to use several different gas targets

PID: \( \pi^+, \pi^-, \pi^0, K^+, K^-, p, \bar{p} \)
It is an experiment which studies the spin structure of the nucleon and not only ...

\[ E = 27.5 \text{ 12 GeV } \text{e}^+ (\text{e}^-) \]

\[ I \sim 30 \text{ mA} \]

p beam of 920 GeV, not used by HERMES

Last part of the fill dedicated to high-density unpolarised target runs:
The Spectrometer

- $e^+$ identification: 99% efficiency and < 1% of contamination
- PID: RICH, TRD, Preshower, e.m. Calorimeter
- For N target: by Cerenkov $\pi$ ID $\ 4<p<14\ GeV$
- For He, Ne, Kr targets: by RICH $\pi, K, p$ ID $\ 2.5<p<15\ GeV$
- $\pi^0$ ID by e.m. Calorimeter.
Particle Identification

Positrons - hadrons separation:

Double radiator RICH: Aerogel + $C_4F_{10}$. Cerenkov photons detected by ~4000 PMTs.

Detection efficiency: 99% ($\pi$), 90% (K), 85-95% (p)
Hadron multiplicity ratio vs transfer energy $\nu$

- Clear nuclear attenuation effect for charged hadrons.
- Increase with $\nu$ consistent with EMC data at higher energy.
- Discrepancy with SLAC due to the *EMC effect*, not taken into account at that time.
- HERMES kinematics is well suited to study quark propagation and hadronization.

HERMES, PLB 577 (2003) 37
SLAC PRL 40 (1978) 1624
Hadron Multiplicity Ratio vs $z = E_h/\nu$

**EMC**

- Cu / D₂
- Sn / D₂

\[ \langle \nu \rangle = 62 \text{ GeV} \]

\[ \langle \nu \rangle = 55 \text{ GeV} \]

**SLAC**

- Be / D₂
- Cu / D₂
- C / D₂
- Sn / D₂

**WA21/WA59**

**HERMES**
**Experimental findings:**

\[ \pi^+ = \pi^- = \pi^0 \sim K^- \]

\[ K^+ > K^- \]

\[ p > \bar{p}, \ p > \pi, \ p > K \]
Multiplicity ratio for identified hadrons vs \( z \)

HerMES, PLB 577 (2003) 37

Different FF modification for quark and anti-quark

Different \( \tau_p \) and \( \tau_h \) for mesons and baryons

Different \( \sigma_h \):
\[
\sigma_{\pi^+} = \sigma_{\pi^-} \approx 20 \text{ mb} \\
\sigma_{K^+} \approx 17 \text{ mb}, \sigma_{K^-} \approx 23 \text{ mb} \\
\sigma_p \approx 40 \text{ mb}, \sigma_{p^-} \approx 60 \text{ mb}
\]
Multiplicity ratio on He, Ne, Kr

Data suggest $\alpha \sim 2/3$
Multiplicity ratio on He, Ne, Kr
Multiplicity ratio vs $Q^2$

$Q^2$ Dependence: indication of FF evolution modification
Stronger at small $\nu$ (large $x$); weaker at high $\nu$ (small $x$)
Hadrons and Pions @ $E_{\text{beam}} = 12 \ & 27$ GeV

Extension of the $\nu$ range down to 2 GeV

- Measurements are still in progress at HERMES
  $2 < \nu < 23$ GeV $Q^2 < 10$ GeV$^2$
Multiplicty Ratio vs $p_t^2$

In pA and AA collisions hadrons gains extra transverse momentum due to the multiple scattering of projectile partons propagating through the nucleus (Cronin effect.)

SIDIS show a $p_t$ enhancement similar to that observed in AA scattering. The enhancement in AA is typically explained at $p_t \sim 1-2$ GeV assuming ISI.

In SIDIS Cronin only from FSI: no multiple scattering of the incident particle nor interaction of its constituents.
$P_t$ dependence for identified hadrons

Dependence of the Cronin effect on the hadron species.
Cronin effect for protons larger than for pions.
Experiments with CLAS and CLAS++

(NIM A503 (2003) 513)

5.4 GeV exp. in 2003
\( Q^2 \leq 4 \text{ GeV}^2, \nu \leq 5 \text{ GeV} \)

11 GeV in 2010-2012
with Jlab upgrade
\( Q^2 \leq 9 \text{ GeV}^2, \nu \leq 9 \text{ GeV} \)

- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution \( \sim 0.5\% \) (charged)
- Angular resolution \( \sim 0.5 \text{ mr} \) (charged)
- Identification of p, \( \pi^+/\pi^- \), K\(^+\)/K\(^-\), e\(^-\)/e\(^+\)
Factorization issues at Jlab

Given the relatively low energy of Jlab (max 6 GeV) the factorization of SIDIS into DF and FF maybe questionable.

\[ \sigma_{eH \to ehX} = \sum_q f_{H \to q} \otimes \sigma_{e\gamma \to q} \otimes D_{q \to h} \]

Cross section reproduced by Monte-Carlo based on LO x-z factorization (Hall C).

Semi-inclusive asymmetry \( A_{1p}^{\pi^+} \) agrees with HERMES, falls on the same curve as inclusive \( A_{1p} \); no z-dependence observed.

LO x-z factorization is not (much) violated at 6 GeV.
Anticipated CLAS Data

Can measure $\pi^{+,−,0}$, $\eta$, $\omega$, $\eta'$, $\phi$, $K^{+,−,0}$, $p$, $\Lambda$, $\Sigma^{+,0}$, $\Xi^{0,−}$
CLAS EG2, very preliminary, 5% of total data set
DIS kinematics, $Q^2>1$, all $\nu$

- No acceptance correction (small, two targets in the beam)
- Not final calibrations (should be nearly irrelevant, bins are huge)
- No fiducial cuts (probably ok, two targets in beam)
- No radiative correction (effect primarily cancels in ratios)
- No correction for $\pi^+$ from rho (need full statistics to correct for this)**
- Few-percent kaon contamination in region 2-2.7 GeV
- No isospin correction for heavy targets (~5%?)
- No $x_F$ cuts

Ask this plot to Will Brooks
brooksw@jlab.org
Expectations from Hall-A E04-002

For fixed kinematics a high precision meas. at large $z$

Figure 8: Attenuation of $\pi^+$ (blue x, larger) and proton (red o, smaller) in carbon (top), copper (central) and tungsten (bottom) as a function of $z$ for $Q^2 = 2.81(\text{GeV}/c)^2$, $\nu = 4 \text{ GeV}$ and $P_T = 0.25 \text{ GeV}/c$. 
Expectations from CLAS++ upgrade
Models based on pre-hadronic interaction


Important role of the pre-hadron formation and interaction:
Which time and cross section? Absorption or rescattering?
Hadron formation mainly outside the nucleus.
Induced radiation is a smaller contribution compared to absorption or rescattering.

Models based on partonic energy loss


Energy loss mechanism for the hadron suppression, parton rescattering for the enhancement at large $p_T$
Gluon Bremsstrahlung

**FF modification:** Nuclear Suppression + Induced Radiation

**Nuclear suppression:** interaction of the $qq$ in the medium.

**Energy loss:** induced gluon radiation by multiple parton scattering in the medium.

---

**Nuclear Suppression**

**Nuclear Suppression + Induced Radiation**
Pre-hadron FSI and formation times

$\tau_p = 0$; $\tau_f > 0.5$ fm/c compatible with data

$R_M$ is very sensitive to the $\sigma_{\text{pre-h}}$; ($\sigma_{\text{pre-h}} = 0.33 \sigma_h$)

T. Falter et al., PLB 594 (2004) 61
and PRC in print, nucl-th/0406023
Rescaling + Absorption Model

\[ \lambda_A > \lambda_N ; \quad \xi_A(Q^2) = \left( \frac{\mu_N^2}{\mu_A^2} \right) \frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)} \]

\[ q_f^A(x, Q^2) = q_f(x, \xi_A(Q^2)Q^2) \]

\[ D_f^{h/A}(z, Q^2) = D_f^h(z, \xi_A(Q^2)Q^2) \]

Nice agreement for p+, p-, K+ with Q^2-rescaling + nuclear absorption (lower curves).
FF modification

multiple parton scattering and induced parton energy loss
(without hadron rescattering)
pQCD approach: LPM interference effect → $A^{2/3}$ dependence

• Consistency with the quadratic nuclear size dependence $[A^{2/3}]^\text{th}$

• 1 free parameter $C \equiv \text{quark-gluon correlation strength in nuclei}$.

• From $^{14}\text{N}$ data $C = 0.0060$ GeV$^2$:

$$\Delta E = n < \Delta z_g > \propto C \alpha_s^2 m_N R_A^2$$
dE/dL and Gluon density at RHIC

$\frac{dE}{dL}_{\text{PHENIX}} |_{\text{Au}}$ predictions determined by using $C=0.0060$ GeV$^2$ from HERMES data.

$<\frac{dE}{dL}> \approx 0.5$ GeV/fm for 10-GeV quark in Au.

PHENIX: hot, expanding system.

HERMES: cold, static system.

$\Downarrow$

- $\Delta E_{\text{sta}} \alpha \rho_0 R_A^2$; $\rho_0$ gluon density and $R_A \approx 6$ fm
- $\Delta E_{\text{exp}} \approx \Delta E_{\text{sta}} (2\tau_0/R_A)$; $\tau_0$ initial formation time of dense medium

• Gluon density in hot matter much higher than in cold matter
FF modification + transport coef.

F. Arleo et al.,
NPA715(2003)899

Soft gluons radiated in the dense QCD medium (gluon transport coefficient from DY)

Energy loss \( \sim 0.6 \text{ GeV/fm} \) in agreement with X-N Wang

Nice agreement with both HERMES and old EMC data
Disentangling hadronic and partonic effects

If only hadronic effect: double-hadron over single hadron ratio is expected to be much smaller in nucleus compared to deuterium.

$$R_{2h}(z_2) = \frac{\left( \frac{d^2N(z_1,z_2)}{dN(z_1)} \right)_A}{\left( \frac{d^2N(z_1,z_2)}{dN(z_1)} \right)_D}$$

Number of events with at least 2 hadrons ($z_{\text{leading}}=z_1>0.5$)

Number of events with at least 1 hadron ($z_1>0.5$)

If only partonic effect: double-hadron over single hadron ratio in nucleus and deuterium is expected to be close to unity.
Two hadron production (prelim.)

- Small effect in $R_{2h}$ compared to single hadron multiplicity
- Small A-dependence (also confirmed by first Xe data)
- Curves from Falter et al. with per-hadronic FSI described with a transport code
- Curve from Majumder et al. (hep-ph/0410078) with partonic energy loss
Two hadron production

- All $h \rightarrow$ rank 1, 2, 3
- No +- and -+ $\rightarrow$ no rank 2, only 1, 3
- Small additional reduction for higher rank (produced before, more inside the nucleus)
Summary and outlook

HERMES is providing new results on hadron production in e-nucleus interaction:

• Nuclear attenuation in a wide kinematical range, vs \( \nu, z, Q^2, p_t^2 \) for \(^4\text{He}, ^{14}\text{N}, ^{20}\text{Ne}, ^{84}\text{Kr} \) (\(^{131}\text{Xe} \) is coming)

• First measurement with identified hadrons: \( \pi^+, \pi^-, \pi^0, K^+, K^-, p, \bar{p} \).

• First observation of hadron-type attenuation.

• First clear observation of the Cronin effect in SIDIS.

• Effect in Ratio of double/single hadron production in \( A \) over \( D \) is small and with almost no \( A \)-dependence.

Measurements are also in progress at Jlab!

• Nuclear modification of the quark Fragmentation Functions
  • Pre-hadronization and final hadronization times
  • Partonic energy loss and scattering