Exploring the Role of Pions in the Nucleus

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• Nuclear forces and “excess” pions
• The ambiguous experimental landscape
  -> DIS and Drell-Yan results
  -> (p,n) Reactions
  -> Pion electroproduction
• New Directions
Pions as Constituents

• QCD describes strong interactions at the most fundamental level
  - hadrons (nucleons) are made of quarks and gluons
• However, cannot generate nucleon parton distributions from 3 quarks + Q^2 evolution
• A meson cloud is required to understand the structure of the nucleon
  - Nucleon axial current partially conserved
  - Ability to extract pion form factor from H(e,e'π^+)
  - Asymmetry of nucleon sea \( \rightarrow \frac{\bar{d}}{\bar{u}} \)
Charged Pion Form Factor from Pion Electroproduction

- No “free pion” target -> extraction of pion form factor at large $Q^2$ requires use of “virtual pion” content of the proton
- Excellent agreement between $\pi^+e$ elastic data and $p(e,e'\pi^+)n$

![Graph showing the relationship between $Q^2F_{\pi}$ and $Q^2$ with data points and curves for different processes.]
Sea-Quark Asymmetry from Drell-Yan

- Fermilab E866 measured D-Y cross section ratios
  \[ \sigma(p + d)/\sigma(p + p) \]
- Extracted results for \( \bar{d} - \bar{u} \) favor pion cloud models

Pions in “Conventional” Nuclear Physics

- Yukawa’s initial insight \( \rightarrow \pi \) as carrier of strong force has proved remarkably durable
- Modern effective NN forces (Bonn, Argonne V-18) are significantly more complex, but the fundamental principle is the same
  - Employ additional mesons (\( \rho \), etc.)
  - Form factors control pion contributions at short distances
  - 3N interactions?
- Effective NN forces work!
  - Green’s Function Monte Carlo calculations accurately reproduce nuclear properties up to \( ^{12}\text{C} \)
  - Only limited by CPU
- These effective theories predict that there should be “extra” virtual pions in the nucleus
The Pion Excess and Pions in the Nucleus

- Using either mean field calculations or detailed N-N forces one can calculate a “pion excess” ->
  \[
  \delta n^A_\pi(k) = n^A_\pi(k) - n^N_\pi(k)
  \]

- Friman et al. used Argonne v28 and found about 0.18 extra pions per nucleon in nuclear matter

- A significant portion of the excess arises from the $\pi N \Delta$ coupling -> with no $\Delta$ states only 0.04 “extra” pions

Friman, Pandharipande, and Wiringa, PRL 51 763 (1983)
Accessing Pions in the Nucleus

- There is a clear indication that the pion cloud of the nucleon is real
- If we are able to access the nucleon pion cloud, we should also be able to access the nuclear pion cloud
- Experimental access to virtual pions in the nucleus
  - Deep Inelastic Scattering (EMC Effect)
  - Drell-Yan Reaction (antiquark distributions in the nucleus)
  - $(\vec{p},\vec{n})$ scattering (Nuclear Longitudinal Response)
  - Pion electroproduction (virtual pion knockout)
Deep Inelastic Scattering – the EMC Effect

- At large $Q^2$, $F_2(x,Q^2) \to F_2(x)$: scattering from constituents
- In pion model one can also scatter from constituents in pions exchanged between nucleons
- Original EMC result (1983) was initially interpreted in this manner
- Enhancement at $x<0.2$ is significantly smaller in later data

Berger-Coester Model of EMC Effect

- Ericson and Thomas:
  - Pion distribution in nucleus, \( f_\pi^A(y) \), calculated in terms of \( R_L(q, \omega) \)

\[
f_\pi^A(y) = \frac{3g^2}{16\pi^2} y \int_{M_N^2}^{\infty} dk^2 \int_0^{k-M_N^2} d\omega \frac{k^2 |G_{pN}(k^2)|^2}{(t+m_\pi^2)^2} R_L(k, \omega)
\]

- B-C calculations links \( f_\pi^A(y) \) directly to pion excess

- Results agrees well with later EMC ratio results down to \( x \sim 0.2 \)


B-C Pion Excess
Nuclear Dependence of Drell-Yan

- Drell-Yan samples antiquark distributions in target
  - should be more sensitive than DIS to pion contributions
- E-772 (FNAL) measured the A dependence of Drell-Yan
- No apparent nuclear dependence
- Appears to rule out models that predict a significant pion excess

D.M. Alde et al., PRL 64 2479 (1990)
Polarization Transfer Reactions

- Pion excess effects on $F_2$ and D-Y come about from enhancement of $R_L(q,\omega)$
- Rather than trying to extract pion excess effects via convolution integral, maybe simpler to measure $R_L(q,\omega)$ directly
- $(\bar{p},n)$ scattering directly sensitive to the isovector part of the nuclear response

J. B. McClelleland et al., PRL 69 582 (1992)
Separated Response Functions in Polarization Transfer

- Initial polarization transfer results inconsistent with RPA calculations that included pion excess effects
  - Only reported ratio of responses
  - No effect expected on $R_T$
- A later extraction of the separated response functions ($R_L$ and $R_T$) hinted at an enhancement of both, but with large systematic errors

Taddeucci et al., PRL 73 3516 (1994)
Quasifree Pion Electroproduction

- Pole process dominates longitudinal cross section
  - Charged $\pi$ production = virtual pion knockout
- JLab exp. E91003 measured charged $\pi$ electroproduction from H,D and $^3$He ($^4$He)
  - Extracted $\sigma_L$ mass dependence
  - 2 values of virtual pion momentum sampled: $k=200, 470$ MeV/c
- Based on Friman et al. calculations, might expect up to 15% effects (25% for $^4$He)
- Uncertainties are too large to confirm or rule out effects from excess pions
Coherent Pion Electroproduction

- Coherent $^3\text{He}(e,e'\pi^+)^3\text{H}$ process can also be used to probe pion field of nucleus
  - In a factorized approximation:
    \[ \sigma(^3H) = \rho F^2(k) \sigma(H) \]
  - $F(k)$ is $^3\text{He}$ form-factor, $\rho$ is kinematic factor
- Results from Mainz and Jlab E91003 hint at an enhancement of the longitudinal strength
  - E91003 compared directly $^3\text{He}$ to $\text{H}$ directly
  - Mainz compared to DWIA calculation using MAID

E91003 $\sigma_L(^3\text{H})/\sigma_L(\text{H})$:
Prediction $\rightarrow 0.42$
Result $\rightarrow 0.50 \pm 0.08$

Mainz: $\sigma_L$ 2x larger than DWIA calculation
Nuclear Pion Scorecard

1. **EMC effect**: maybe
   - Calculations including pion excess can do a good job down to $x \sim 0.2$
   - These models predict significant effects in Drell-Yan scattering

2. **Drell-Yan**: no
   - All models including significant pion effects inconsistent with E772 data
   - A reduced pion content is allowed (G. Miller), but then convolution EMC calculations suffer
   - Not a problem if we’re happy to introduce more exotic physics at moderate $x$ ($\sim 0.2-0.6$)

3. **Polarization transfer**: maybe
   - Separated response functions consistent with pion excess calcs., but large error bars

4. **Pion Electroproduction**: maybe
   - Quasifree production needs smaller errors and $^4$He
   - Coherent production tantalizing, but not really conclusive
Pions are in Nucleons - What About Nuclei?

• There are experimental indications that the pion cloud plays a significant role in nucleon structure.

• Why can we not see similar effects in nuclei?

• Either we need totally new probes, or we're misusing the probes we have.
New Directions

• If pion excess leads to enhancement of antiquark distributions and we can’t see that at low $x$, maybe we need to go higher?
  - Drell-Yan at higher $x$
    • Fermilab E906 will measure Drell-Yan at larger $x$
  - Separated inclusive cross sections
    • G. Miller predicts large effects for the $A$-dependence of $\sigma_L$ at moderate $x$ ($\sim 0.4$)

• JLab at 12 GeV
  - (EMC Effect at large $x$)
  - Semi-inclusive production
  - More exclusive and semi-exclusive pion electroproduction
Fermilab E906

- Approved Fermilab E906 will extend precision and x-range of E772 Drell-Yan measurements
- If B-C model has correct trend but wrong absolute value, should be able to discern by going to larger x
- Date of E906 run still TBD
Inclusive Electron Scattering

- G. Miller light front calculation predicts large effects in the inclusive, longitudinal cross section
- Accurately reproduces existing D-Y data -> requires rather modest pion excess (~0.05/nucleon)
- JLab E02-109 and E04-001 will measure L-T separated cross sections where effect predicted to be large
- E91003 measured exclusive pion production at Q2=0.4, x=0.48 and saw no indication of such large effects - ³He not heavy enough?

Semi-inclusive Production from Nuclei

- Explore $\nu$ and $z$ dependence of hadronization effects at $x \sim 0.3$ (no EMC effect)
- Use semi-inclusive meson production to explore flavor specific EMC effect or nuclear dependence of sea asymmetry
Nuclear Response at Large Virtual Pion Energies

- Size of the pion excess can be related to the spin-isospin longitudinal nuclear response

\[
\delta n^A_\pi(k) = \frac{f^2 F^2(k)}{2\varepsilon_k} \int_0^\infty d\omega \frac{R_L(k,\omega)}{[\varepsilon_k + \omega]^2} - n^N_\pi(k)
\]

- In NN correlated theory, much of the excess pion strength appears at large virtual pion energy, \(\omega \rightarrow D. Koltun, Phys. Rev. C 57, 1210 (1998)\)

- Large \(\omega\) contributions suppressed in the convolution integrals used for calculating light-cone pion distribution in nuclei

\[
f^A_\pi(y) = \frac{3g^2}{16\pi^2} y \int_{M_{NN}}^\infty dk^2 \int_0^{k-M_{NN}} dk \frac{k^2 |G_{\pi NN}(k^2)|^2}{(t+m^2_\pi)^2} R_L(k,\omega)
\]

- Pion electroproduction at large missing mass (\(z<1\)) can probe the longitudinal response at large \(\omega\)
(Semi-) Exclusive Pion Electroproduction

- In parallel kinematics, exclusive pion electroproduction from nuclei samples a contour in virtual pion energy and momentum space.
- If restricted to exclusive production (below 2-pion threshold) will never measure large $\omega$.
- Must map out transition between semi-inclusive and exclusive nucleon/deuteron (longitudinal and transverse!)
- Compare $z<1$ in nuclei to calculations that include:
  1. Quasifree pion production
  2. $z<1$ pion production from nucleon.

- Missing mass spectrum for (quasifree) $\pi^-$ production from $^3$He.

2-pion threshold
Pion Electroproduction at 12 GeV

- Advantages of 12 GeV JLab for pion electroproduction search for nuclear pions
  - At z<1, higher energies will reduce resonance effects in residual system -> simplify model calculation of quasifree+fragmentation components of electroproduction cross section in nuclei
  - At higher energies, color transparency may allow us to use heavier nuclei. Currently limited to light nuclei ($^3$He, $^4$He) because of pion re-scattering effects
Summary

- Pions seem to be an intrinsic, non-perturbative part of nucleon structure.
- Conventional pictures of the strong force at large and medium distance scales require pions to be the force "carrier".
- These theories predict that there should be "extra" pions in the nucleus.
- To date, there is no convincing experimental evidence these "nuclear pions" have been observed.
- JLab at 12 GeV
  - EMC Effect at large $x$
  - Semi-inclusive studies
  - $L-T$ separated exclusive and semi-inclusive cross sections