Forward neutrons from polarized $pA$ collisions

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Neutron production in the vicinity of pion pole

\[ p + p \rightarrow n + X \]

\[ z = \frac{p_n^+}{p_p^+} \rightarrow 1 ; \quad M_X^2 = (1 - z)s \]

\[ A_{p\rightarrow n}^B(\tilde{q}, z) = \bar{\xi}_n \left[ \sigma_3 Q_L + \frac{1}{\sqrt{z}} \tilde{\sigma} \cdot \tilde{q}_T \right] \xi_p \phi^B(q_T, z) \]

\[ \phi^B(q_T, z) = \frac{\alpha'_\pi}{8} G_{\pi^+ p n}(t) \eta_\pi(t)(1 - z)^{-\alpha_\pi(t)} A_{\pi^+ p \rightarrow X}(M_X^2) \]

\[ z \frac{d\sigma_{p\rightarrow n}^B}{dz dq_T^2} = \frac{g_{\pi^+ p n}^2}{(4\pi)^2 (m_\pi^2 - t)^2} |t| F^2(t) (1 - z)^{1 - 2\alpha_\pi(t)} \sigma_{tot}^{\pi^+ p}(M_X^2) \]

\[ q_L = \frac{1 - z}{\sqrt{z}} m_N \]

\[ t = -q_L^2 - q_T^2 / z \]
Results

Underestimated theory, or overestimated data?

The main suspect is the normalization of the ISR data.
Results

Leading neutrons from DIS on protons $\gamma^* p \rightarrow nX$ offer a unique way to measure the pion structure function at small $x$.

Neutron production off nuclei

At first glance, is sufficient to replace $\sigma_{\text{tot}}^{p}$ by $\sigma_{\text{tot}}^{A}$

$$
\frac{d\sigma^B}{dzdq_T} = \frac{g^2}{(4\pi)^2} \frac{F^2(t)}{m^2 - t} (1 - z)^{1-2\alpha(t)} \sigma_{\text{tot}}^{A}(M^2_X)
$$

However, absorption is order of magnitude stronger, compared with $pp \rightarrow nX$

$$
\frac{\sigma(pp \rightarrow nX)}{A \sigma(pp \rightarrow nX)} = \frac{2}{\sigma_{\text{tot}}^{p}} \int d^2b \left[ 1 - e^{-\frac{1}{2}\sigma_{\text{tot}} T_A(b)} \right] e^{-\sigma_{\text{NN}} T_A(b)}
$$

If BBC are fired detecting multiparticle production, one should replace

$$
2 \left[ 1 - e^{-\frac{1}{2}\sigma_{\text{tot}} T_A(b)} \right] \Rightarrow 1 - e^{-\sigma_{\text{in}} T_A(b)}
$$

If BBC are vetoed, the diffractive channels $p + A \rightarrow n\pi^+ + A^*$ dominate, i.e. $\pi A \rightarrow X$ should be replaced by elastic and quasielastic cross sections,

$$
2 \left[ 1 - e^{-\frac{1}{2}\sigma_{\text{tot}} T_A(b)} \right] \Rightarrow \left[ 1 - e^{-\frac{1}{2}\sigma_{\text{tot}} T_A(b)} \right]^2 + \sigma_{\text{el}}^{\pi N} T_A(b) e^{-\sigma_{\text{in}}^{\pi N} T_A(b)}
$$

elastic $\pi A$

quasielastic $\pi A$
Cross sections

Three different channels of neutron production:

(i) inclusive neutrons;
(ii) multi-particle production (BBC fired);
(iii) rapidity gap diffractive events (BBC vetoed)
Single-spin asymmetry

The pion-exchange amplitude includes both non-flip and spin-flip terms

\[ A_{p \to n}^B(\tilde{q}, z) = \xi_n \left[ \sigma_3 q_L + \frac{1}{\sqrt{z}} \vec{\sigma} \cdot \vec{q}_T \right] \xi_p \phi^B(q_T, z) \]

Both amplitudes have the same phase

\[ \eta_\pi(t) = i - \text{ctg} \left[ \frac{\pi \alpha_\pi(t)}{2} \right] \]

No single-spin asymmetry is possible

Interference with other Reggeons

Only unnatural parity states can be produced diffractively

\[ A(\pi p \to \tilde{a}_1 p) \approx \text{const} \]

\[ \tilde{a}_1 = a_1, \rho \pi, ... \]
\[ A_{N}^{(\pi-a_1)}(q_T, z) = q_T \frac{4m_N q_L}{|t|^{3/2}} (1 - z)^{\alpha_\pi(t) - \alpha_{a_1}(t)} \frac{\text{Im} \eta_{\pi}^*(t) \eta_{a_1}(t)}{|\eta_{\pi}(t)|^2} \]

\[ \times \left( \frac{d\sigma_{\pi p \rightarrow a_1 p}(M_X^2)}{dt}|_{t=0} \right)^{1/2} \frac{g_{a_1^+pn}}{g_{\pi^+pn}} \]

Three inputs:
- From pion diffractive data
- Regge-cut trajectory \( \alpha_{\bar{a}_1}(t) \)
- \( a_1 \)-nucleon coupling \( g_{a_1 np} \)

PCAC and the 2d Weinberg sum rule:
\[ \frac{g_{a_1 NN}}{g_{\pi NN}} = \frac{m_{a_1}^2 f_\pi}{2m_N f_\rho} \approx 0.5 \]

The parameter-free calculations agree with the PHENIX data.
Astonishing spin effects in pA→nX

Recent measurements by PHENIX of the single-spin asymmetry of neutrons from polarized pA collisions revealed a weird A-dependence.

BBC triggering sheds light on this mystery.

Inclusive production

Inelastic events

A (atomic mass number)

\( A^N \) in p+Au → n+X

- \( p^+A \rightarrow n+X \)
  - \( \vec{p}=200 \text{ GeV} \)
  - \( x_p>0.5 \)
  - \( 0.3<\theta<2.2 \text{ mrad} \)
  - 22% scale uncertainty not shown
\[ A_N \text{ in } pA \rightarrow nX \]

\[
A_{N_{pA \rightarrow nX}}^{pA \rightarrow nX}(q_T, z) = q_T \frac{4m_N q_L}{|t|^{3/2}} (1 - z)^{\alpha_\pi(t) - \alpha_\bar{\alpha}_1(t)} \frac{\text{Im} \eta_\pi^*(t) \eta_\bar{\alpha}_1(t)}{|\eta_\pi(t)|^2}
\]

The only difference
with pp -> nX

\[
\left( \frac{d\sigma_{\pi A \rightarrow \bar{\alpha}_1 A} (M_X^2)}{dt}|_{t=0} \right)^{1/2} \frac{g_{\bar{\alpha}_1^+ pn}}{g_{\pi^+ pn}}
\]

\[
A_{N_{pA \rightarrow nX}}^{pA \rightarrow nX} = A_{N_{pp \rightarrow nX}}^{pp \rightarrow nX} \times \frac{R_1}{R_2} R_3
\]

Nuclear and trigger effects

Nuclear effects for coherent \( \pi + A \rightarrow \pi + p + A \)

\[
R_1 = \frac{1}{\sigma_{pp \rightarrow pA}^{\text{tot}}} \int d^2b \ e^{-\frac{1}{2} \sigma_{\pi A}^{\text{pp}} T_A(b)} \left[ 1 - e^{-\frac{1}{2} \sigma_{\pi A}^{\text{pp}} T_A(b)} \right] e^{-\frac{1}{2} \sigma_{\pi A}^{\text{pp}} T_A(b)}
\]

Nuclear effects for the denominator \( \pi A \rightarrow \pi A \)

Absorption factors

\[
R_2 = \frac{2}{\sigma_{\pi A}^{\text{tot}}} \int d^2b \left[ 1 - e^{-\frac{1}{2} \sigma_{\pi A}^{\text{pp}} T_A(b)} \right] e^{-\frac{1}{2} \sigma_{\pi A}^{\text{pp}} T_A(b)}
\]

Triggering on nuclear breaks-up

\[
R_3 = \frac{\sigma_{\pi A}^{\text{tot}}}{\sigma_{\pi A}^{\text{in}}}
\]

Nuclear and trigger effects
$A_N$ in $pA \rightarrow nX$

Incoherent production: the nucleus breaks up, the BBC_S is fired

This sample of events with nuclear break-up is reasonably well explained.

However, the large positive values of $A_N$ in rapidity-gap events remain unexplained.
A peculiar feature of the rapidity gap events is the extremely small invariant mass $M$ of the diffractive excitation $p \rightarrow n\pi$.

$$M^2 = \frac{m_n^2}{z} + \frac{m_\pi^2}{1-z} + \frac{q_T^2}{z(1-z)} = (1.15 \text{ GeV})^2$$

The overall momentum transfer in coherent production $p_T^2 \sim 1/R_A^2 = 0.0008 \text{ GeV}^2$ is small compared with the measured neutron $\langle q_T^2 \rangle = 0.013 \text{ GeV}^2$, and is even much less in Coulomb excitation.

Neglecting $q_T$, and fixing $z=0.75$, the invariant mass is very small, too small to relate to the polarized Primakoff effect.
Summary

- First calculations of leading neutron production off nuclei are done for coherent, diffractive, and incoherent events. The fraction of rapidity-gap events is found to be 25%, nearly independent of $A$.

- The nuclear effects for $A_N$ of leading neutrons due to $\pi - \tilde{a}_1$ interference are calculated in good agreement with data for incoherent neutron production, associated with a nuclear break-up.

- While the cross section of leading neutron production agrees well with the single pion model, the spin effects are more involved and require contribution of other mechanisms, e.g. $\pi - \tilde{a}_1$ interference.
The $a_1$ is a weak pole: no axial-vector dominance for the axial current.

Nevertheless, the invariant mass distribution of diffractively produced $\pi-\rho$ in $1^+S$ state forms a peak, dominated by the Deck mechanism, with a similar position and width as $a_1$. This singularity in the dispersion relation can be treated as an effective pole “a” with mass $m_a = 1.1$ GeV.

The cross section of $\pi + p \rightarrow (\pi \rho)_{1^+S} + p$ was measured up to 94 GeV.

$$\frac{d\sigma_{\pi p \rightarrow a p}(E_{lab} = 94 \text{ GeV})}{dq_T^2} \bigg|_{q_T=0} = 0.8 \pm 0.08 \frac{\text{mb}}{\text{GeV}^2}$$

Extrapolated to the RHIC energy range correcting for absorption.
PCAC miraculously relates the pion-nucleon coupling with the axial constant

\[ g_{\pi NN} = \frac{\sqrt{2m_N} G_A}{f_\pi} \]

Goldberger-Treiman relation

\[ G_A = \frac{\sqrt{2f_a g_{aNN}}}{m_a^2} \]

\[ f_a = f_\rho = \frac{\sqrt{2m^2}}{\gamma_\rho} \]

The dispersion integrals for vector and axial currents are related by the 2d Weinberg sum rule

Thus,

\[ \frac{g_{aNN}}{g_{\pi NN}} = \frac{m_a^2 f_\pi}{2m_N f_\rho} \approx 0.5 \]
Assuming the universal slope of Regge trajectories $\alpha'_{a_1} = 0.9$ GeV$^{-2}$

$$\alpha_{a_1}(t) = -0.43 + 0.9t$$

The $\pi-\rho$ cut state is more important, it has trajectory

$$\alpha_{\pi-\rho}(t) = \alpha_{\pi}(0) + \alpha_{\rho}(0) - 1 + \alpha'_{R} t/2$$

The signature factor of the effective $1^+ S$ state

$$\eta_a(t) = -i - tg\left[\pi \alpha_a(t)/2\right]$$

The phase shift relative the pion pole is large

$$\phi_a(t) - \phi_{\pi}(t) \approx \frac{\pi}{2} \left[1.5 + 0.45t\right]$$