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Azimuthal asymmetry of neutrons produced by polarized protons

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Summary. — The transverse single-spin asymmetry $A_N(t)$, for inclusive leading neutron production in polarised pp collisions is calculated in the energy range of RHIC. Absorptive corrections to the pion pole generating a relative phase between the spin-flip and non-flip amplitudes, are found to be insufficient to explain the magnitude of A_N observed recently in the PHENIX experiment. A larger contribution, comes from the interference of pion and the effective a-Reggeon, which includes the a_1 pole and the (dominant) $\pi\rho$ Regge cut. Assuming that this state saturates the spectral function of the axial current we determined its coupling to the nucleons applying the PCAC and the 2d Weinberg sum rule. The results of the parameter-free calculation of A_N are in excellent agreement with the PHENIX data.

PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 11.80.Cr – Helicity amplitudes.
PACS 11.80.Gw – Multichannel scattering.
PACS 13.88.+e – Polarization in particle interactions.

1. – Introduction

The mechanism of forward neutron production in pp and γ^*p interactions has been always considered as a way to single out the pion exchange contribution [1]. The pion Regge trajectory has a low intercept $\alpha_\pi(0) \approx 0$, this is why it ceases to be important at high energies in binary reactions. A different situation takes place in inclusive reactions, which are known to have (approximate) Feynman scaling, and as a consequence the pion contribution to neutron production remains nearly unchanged with energy. This can be seen from the graphical representation of the cross section of the inclusive reaction $h + p \to X + n$ in fig. 1.

The pion pole dominance is not obvious. Indeed, in order to decrease the 4-momentum transfer squared t and get closer to the pion pole, one should select neutrons with higher possible fractional momentum $z \to 1$ of the neutron (see below). Simultaneously the

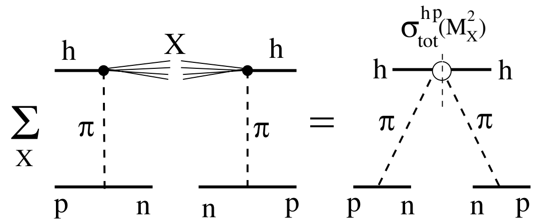

Fig. 1. – Graphical representation of the cross section of inclusive neutron production in hadron-proton collisions, in the fragmentation region of the proton.

pion exchange acquires a larger rapidity interval, and the competing Regge exchanges with higher intercepts become important.

Polarization effects have always been known as a sensitive probe for interference between different contributions. The single-transverse-spin asymmetry in reaction $pp \to nX$ with polarized protons was measured recently by the PHENIX experiment at RHIC [2] in pp collisions at energies $\sqrt{s} = 62,\ 200$ and $500\,\mathrm{GeV}$. The measurements were performed with a transversely polarized proton beam, and the neutron was detected at very forward and backward rapidities relative to the polarized beam. An appreciable single-transverse-spin asymmetry was found in events with large fractional neutron momenta z. The data agree with a linear dependence on the neutron transverse momentum q_T, and different energy match well, what indicates at an energy-independent $A_N(q_T)$.

Below we demonstrate that the large magnitude of the single-transverse-spin asymmetry of forward neutrons discovered in [2], reveals a new important mechanism of neutron production ignored in previous studies of this process.

2. – Single-spin asymmetry of forward neutrons

Contrary to the conventional wisdom, the pion-nucleon vertex is not pure spin-flip, but a large non-flip term in the amplitude appears if the fractional light-cone momentum of the neutron $z < 1$. In Born approximation the pion exchange in neutron production, depicted in fig. 1, in the leading order in the small parameter $m_N/\sqrt{s}$ has the form [3],

$$A^B_{p\to n}(\vec{q}, z) = \bar{\xi}_n \left[\sigma_3\, q_L + \frac{1}{\sqrt{z}}\,\vec{\sigma}\cdot\vec{q}_T\right] \xi_p\, \phi^B(q_T, z)\,, \tag{1}$$

where $\vec{\sigma}$ are the Pauli matrices; $\xi_{p,n}$ are the proton or neutron spinors; $\vec{q}_T$ and

$$q_L = \frac{1-z}{\sqrt{z}}\, m_N\,, \tag{2}$$

are the transverse and longitudinal components of the momentum transfer respectively.

At large z the pseudoscalar amplitude $\phi^B(q_T, z)$ has the Regge form [4],

$$\phi^B(q_T, z) = \frac{\alpha'_\pi}{8}\, G_{\pi^+pn}(t)\, \eta_\pi(t)\, (1-z)^{-\alpha_\pi(t)} A_{\pi^+p\to X}(M_X^2)\,, \tag{3}$$

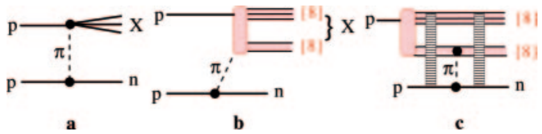

Fig. 2. – a: Born graph with single pion exchange; b: inelastic proton-pion interaction via color exchange, with production of two color-octet dipoles; c: Fock state representation of the previous mechanism, complemented with initial/final state interactions.

where $M_X^2 = (1-z)s$; the 4-momentum transfer squared (t) has the form,

$$-t = q_L^2 + \frac{1}{z}\, q_T^2. \tag{4}$$

Both spin-flip and non-flip amplitudes in (1) have the same phase, given by the signature factor,

$$\eta_\pi(t) = i - \mathrm{ctg}\left[\frac{\pi\alpha_\pi(t)}{2}\right], \tag{5}$$

where the second term in (5) contains the pion pole,

$$\mathrm{Re}\,\eta_\pi(t) \approx \frac{2}{\pi\alpha'_\pi}\,\frac{1}{m_\pi^2 - t}\,. \tag{6}$$

In what follows we assume that the pion Regge trajectory is a linear function of t, $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$, where $\alpha'_\pi \approx 0.9\,\mathrm{GeV}^{-2}$.

The effective vertex function in (3) is parametrized as,

$$G_{\pi^+pn}(t) = g_{\pi^+pn}\, e^{R_\pi^2 t}, \tag{7}$$

where the pion-nucleon coupling $g^2_{\pi^+pn}/8\pi = 13.85$. The t-slope parameter R_π^2 incorporates the t-dependences of the coupling and of the πN inelastic amplitude. Although it is not well known, its value is not really important for us, since we concentrate on the small t region. For further calculations we fix $R_\pi^2 = 4\,\mathrm{GeV}^{-2}$, which is naturally related to the nucleon size.

The amplitude (1) is normalized as $M_X^2 \sigma_{tot}^{\pi^+p} = \sum_X |A_{\pi^+p\to X}(M_X^2)|^2$. Correspondingly, the differential cross section of inclusive neutron production reads,

$$z\,\frac{\mathrm{d}\sigma^B_{p\to n}}{\mathrm{d}z\, dq_T^2} = \left(\frac{\alpha'_\pi}{8}\right)^2 |t| G^2_{\pi^+pn}(t)\, |\eta_\pi(t)|^2\, (1-z)^{1-2\alpha_\pi(t)} \sigma_{tot}^{\pi^+p}(M_X^2)\,. \tag{8}$$

This pure pion pole model has two obvious shortcomings: i) the cross section eq. (8) substantially overshoots data [3]; ii) no single transverse-spin asymmetry is possible because the spin-flip and non-flip terms in the amplitude (1) have no phase shift.

The first problem was settled in [3] by introducing the absorptive corrections corresponding to initial/final state interactions of the projectile partons. This is illustrated pictorially in fig. 2c. It was demonstrated that the suppression factor caused by absorption is very large, because it is related to the propagation of a strongly interacting 5-quark

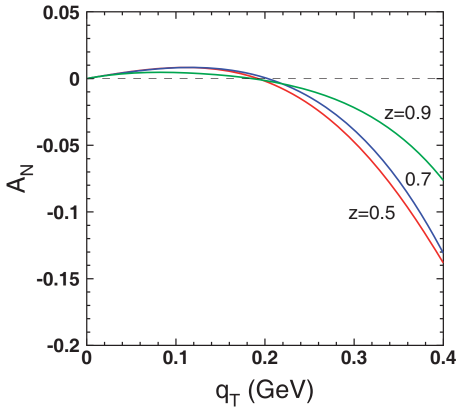

Fig. 3. – Single-transverse-spin asymmetry of leading neutrons related to the single-pion exchange corrected for absorptive corrections, as function of q_T. The curves from bottom to top correspond to $z = 0.5,\ 0.7$ and 0.9.

color octet-octet dipole. This brings the cross section, which considerably overestimates data within the single pole approximation, down to the right magnitude. However, the calculated phase shift between the spin-flip and non-flip amplitudes was found to be too small to explain the PHENIX data on A_N. The results of calculations [5,6] are depicted in fig. 3. Apparently, the calculated asymmetry is far too small to explain the PHENIX results depicted in fig. 4.

3. – Axial-vector Reggeons and Regge cuts

In addition to pion exchange, other Regge poles $R = \rho,\ a_2,\ \omega,\ a_1$, etc. and Regge cuts can contribute to the $pp \to nX$ reaction as is illustrated graphically in fig. 5.

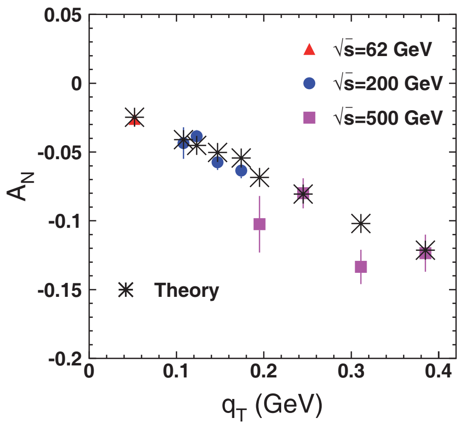

Fig. 4. – Single-transverse-spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500\,\mathrm{GeV}$ [2] (preliminary data). The asterisks show the result of our calculation, eq. (22).

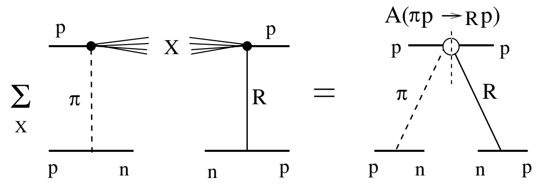

Fig. 5. – Graphical representation for the interference between the amplitudes with pion and Reggeon exchanges.

Summing over different produced states X and using completeness one arrives at the imaginary part of the amplitude of the process $\pi + p \to R + p$ at c.m. energy M_X^2. The production of natural parity states, like ρ, a_2, etc. can proceed only via Reggeon exchange, therefore these amplitudes are strongly suppressed at RHIC energies by a power of M_X (dependent on the Regge intercept) and can be safely neglected everywhere, except the region of very small $(1-z) \sim s_0/s$, unreachable experimentally.

Only the unnatural parity states, which can be diffractively produced by a pion, like the a_1 meson, or ρ-π in the axial vector or pseudo-scalar states, contribute to the interference term in the neutron production cross section at high energies.

The a_1NN vertex is pure non spin-flip [7,8], therefore, it should be added to the first term in eq. (1),

$$A^{a_1}_{p\to n}(q_T, z) = e^L_\mu\, \bar{n}\, \gamma_5 \gamma_\mu\, p = \frac{2m_N q_L}{\sqrt{|t|}}\, \phi^a_0(q_T, z)\, \bar{\xi}_n \sigma_3 \xi_p, \tag{9}$$

where the longitudinal polarization vector of a_1 reads [9],

$$e^L_\mu = \frac{1}{\sqrt{|t|}} \left(\sqrt{q_0^2 - t},\, 0,\, 0,\, q_0\right), \tag{10}$$

and the transferred energy

$$q_0 = E_p - E_n = q_L + O\big(m_N/\sqrt{s}\,\big)\,. \tag{11}$$

In the Born approximation,

$$\phi^a_0(q_T, z) = \frac{\alpha'_{a_1}}{8}\, G_{a^+pn}(t)\, \eta_{a_1}(t)(1-z)^{-\alpha_{a_1}(t)} A_{a_1^+ p \to X}(M_X^2)\,, \tag{12}$$

and

$$\eta_{a_1}(t) = -i - tg\left[\frac{\pi\alpha_{a_1}(t)}{2}\right]. \tag{13}$$

The amplitude (9) contains three unknowns, which we fix as follows.

3˙1. *The amplitude* $A_{a_1^+ p\to X}(M_X^2)$. – The amplitude $A_{a_1^+ p\to X}(M_X^2)$ is normalized as,

$$\sum_X A^\dagger_{a_1^+ p\to X}(M_X^2)\, A_{\pi p\to X}(M_X^2) = 4\sqrt{\pi}\, M_X^2 \sqrt{\mathrm{d}\sigma(\pi p\to a_1 p)/\mathrm{d}p_T^2|_{p_T=0}}\,. \tag{14}$$

The a_1 pole is very weak, it has been observed in $\pi\to 3\pi$ diffraction only by means of a phase-shift analysis [10, 11].

A much large contribution comes from the axial-vector state $\rho\pi(1^+S)$, which has the invariant mass distribution forming a strong and narrow peak at $M_{\pi\rho}\approx 1.1\,\mathrm{GeV}$, related mainly to the Deck mechanism [12].

The magnitude and energy dependence of the diffractive cross section, $\pi + p \to \rho\pi(1^+S) + p$ has the form,

$$\frac{\mathrm{d}\sigma_{sd}(M_X^2)}{\mathrm{d}q_T^2} = \frac{\mathrm{d}\sigma_{sd}(s_1)}{\mathrm{d}q_T^2}\left(\frac{M_X^2}{s_1}\right)^{0.16}\frac{K_{\pi p}(M_X^2)}{K_{\pi p}(s_1)}\,, \tag{15}$$

where the first factor was fitted in [6] to data [11] at the energy $s_1 \sim 119-177\,\mathrm{GeV}^2$. Equation (15) extrapolates it up to the substantially higher c.m. energies $M_X^2 = (1-z)s$ of RHIC.

The $K(s)$ in (15) is the survival probability of a large rapidity gap, which in the eikonal approximation has the form [13]

$$K_{\pi p}(s) = 1 - \frac{1}{\pi}\,\frac{\sigma_{tot}^{\pi p}(s)}{B_{sd}^{\pi p}(s) + 2B_{el}^{\pi p}(s)} + \frac{1}{(4\pi)^2}\,\frac{\left[\sigma_{tot}^{\pi p}(s)\right]^2}{B_{el}^{\pi p}(s)\left[B_{sd}^{\pi p}(s) + B_{el}^{\pi p}(s)\right]}\,, \tag{16}$$

where the elastic and single diffractive slopes are $B^{\pi p}(s) = B_0 + 2\alpha'_{I\!P}\ln(s/s_0)$, with $B_0 = 6\,\mathrm{GeV}^{-2}$ for elastic and $B_0 = 9\,\mathrm{GeV}^{-2}$ for single diffractive processes.

Since we found that the production cross section for the a_1 meson is too small to produce a sizable contribution to neutron production, it should be complemented with the more significant production of a $\pi\rho$ 1^+S state, which forms a narrow resonance-like peak in the 3π invariant mass distribution. So, we introduce and employ in what follows the effective "pole" a in the dispersion relation for the axial-vector current, and predict its production cross section in πp collisions at high energies.

3˙2. *The a-nucleon vertex* $G_{aNN}(t)$. – Like for the pion we parametrize the a_1-nucleon vertex in eq. (12) as $G_{a^+pn}(t) = g_{a^+pn}\exp(R_a^2\, t)$. The slope parameter R_a^2 is poorly known, however in the small t region under consideration it is not of great importance. Like for the pion vertex, it is natural to expect the slope to be related to the nucleon size, so we fix $R_a^2 = R_\pi^2 = 4\,\mathrm{GeV}^2$ for further calculations.

The a-nucleon coupling g_{a^+pn} can be estimated based on PCAC. Although it is tempting to interpret the Goldberger-Treiman relation and Adler theorem as pion pole dominance, the pion pole does not contribute in either β-decay or high-energy neutrino interactions, because of conservation of the lepton current (neglecting the lepton mass) [9, 14]. In order to have PCAC heavy axial states contributing to the dispersion relation for the amplitude of the process must miraculously reproduce the pion pole. If we replace the combined contribution of the heavy state by an affective pole a [9,15,16], the Goldberger-Treiman relation relates the a and pion poles,

$$\frac{\sqrt{2}f_a\, g_{aNN}}{m_a^2} = \frac{f_\pi\, g_{\pi NN}}{\sqrt{2}m_N}\,. \tag{17}$$

In the second Weinberg sum rule the spectral function of the vector current can be represented by the ρ-meson pole. Correspondingly, the axial spectral function is saturated by the effective a meson, because the pion does not contribute to the second Weinberg sum rule. Then one arrives at the relation,

$$f_a = f_\rho = \frac{\sqrt{2}m_\rho^2}{\gamma_\rho}\,, \tag{18}$$

where γ_ρ is the universal coupling (ρNN, $\rho\pi\pi$, etc.), $\gamma_\rho^2/4\pi = 2.4$.

Thus, for the a to pion couplings ratio we get,

$$\frac{g_{aNN}}{g_{\pi NN}} = \frac{m_a^2\, f_\pi}{2m_N\, f_\rho} \approx 0.5. \tag{19}$$

3$\cdot$3. *Regge trajectory of the "a-pole"*. – So far the narrow a-peak in the spectral function of the axial current could be treated as an effective pole replacing the real one a_1, which was found to be too weak. However, the Regge singularity in the complex angular momentum plane, related to the π-ρ exchange, is a Regge cut rather than a pole. The trajectory of the cut can be expressed in terms of the π and ρ Reggeons,

$$\alpha_{\pi\rho}(t) = \alpha_\pi(0) + \alpha_\rho(0) - 1 + \frac{\alpha'_\pi\alpha'_\rho}{\alpha'_\pi + \alpha'_\rho}\, t. \tag{20}$$

For further numerical evaluations we fix $\alpha(0) = 1/2$ and $\alpha'_\pi = \alpha'_\rho = 0.9\,\mathrm{GeV}^{-2}$, so $\alpha_{\pi\rho}(t) = -0.5 + 0.45t$.

Correspondingly, the phase (signature) factor for the unnatural parity a-Reggeon exchange reads,

$$\eta_a(t) = -i - tg\left[\pi\alpha_a(t)/2\right], \tag{21}$$

where $\alpha_a(t) = \alpha_{\pi\rho}(t)$.

This factor provides a significant phase shift $\Delta\phi = \pi/4$ relative to the pion, and this phase shift rises with t up to the maximal value of $\pi/2$ at $t = -1\,\mathrm{GeV}^2$. This interference looks like a promising source of a significant single transverse-spin asymmetry.

Notice that the intercept of the π-ρ cut turns out to be rather close to the intercept of the a_1 Regge pole, $\alpha_{a_1}(0) = -0.43$, which corresponds to a straight Regge trajectory with the universal slope crossing the position of the a_1 pole on the Chew-Frautschi plot.

Eventually, we are in a position to perform a parameter free calculation of the a-π interference contribution to the single transverse-spin asymmetry of neutron production,

$$A_N(q_T, z) = q_T\, \frac{4m_N\, q_L}{|t|^{3/2}}\,(1-z)^{\Delta\alpha(t)}\,\frac{\mathrm{Im}\,\eta_\pi^*(t)\,\eta_a(t)}{|\eta_\pi(t)|^2}\,\frac{g_{a^+pn}}{g_{\pi^+pn}}\left(\frac{\mathrm{d}\sigma_{\pi p\to ap}(M_X^2)/\mathrm{d}p_T^2|_{p_T=0}}{\mathrm{d}\sigma_{\pi p\to\pi p}(M_X^2)/\mathrm{d}p_T^2|_{p_T=0}}\right)^{1/2}, \tag{22}$$

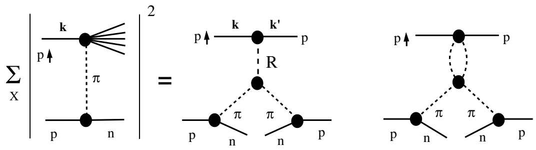

Fig. 6. – Graphical representation of the cross section of inclusive reaction $p\uparrow + p \to X + n$.

where $\Delta\alpha(t) = \alpha_\pi(t) - \alpha_a(t)$. The results of calculations for every value of z corresponding to the experimental point, are plotted by asterisks in fig. 4. They agree well with the PHENIX data. Notice that the estimated uncertainty of our calculations is about 30%.

4. – A_N in the backward hemisphere

The PHENIX measurements [2] found that neutrons produced with large $x_F < 0$ have a small azimuthal asymmetry, consistent with zero. This fact is explained by the so called Abarbanel-Gross theorem [17] which predicts zero transverse-spin asymmetry for particles produced in the fragmentation region of an unpolarized beam. This statement was proven within the Regge pole model illustrated in fig. 6a,b.

The amplitude of the reaction $p\uparrow + p \to X + n$ squared, fig. 6a, is related by the optical theorem with the triple-Regge graph in fig. 6b. According to Regge factorization the proton spin can correlates only with the vector product, $[\vec{k} \times \vec{k}']$, of the proton momenta in the two conjugated amplitudes, as is shown in fig. 6b. According to the optical theorem these momenta are equal, $\vec{k} = \vec{k}'$, so no transverse-spin correlation is possible. Regge cuts shown in fig. 6c breakdown this statement, but the magnitude of the gained single-spin asymmetry calculated in [18], turns out to be very small, less than 1%.

5. – Summary

Although the cross section of leading neutron production in pp collisions at high energies is well explained by the pion pole exchange supplemented with (significant) absorptive corrections, this description fails to reproduce the magnitude of the transverse single-spin asymmetry in polarized pp collisions, measured recently by the PHENIX collaboration at RHIC.

Another possible source of spin effects is the interference between the amplitudes of neutron production via pion and a_1 Reggeon exchanges. Because a_1 has unnatural parity, it can be produced diffractively in $\pi + p \to a_1 + p$, so is not suppressed at high c.m. energy M_X. It also provides a large, close to maximal, relative phase shift between the non-flip a_1 and spin-flip pion exchange amplitudes.

It turns out, however, that the a_1 exchange contribution is strongly suppressed by the smallness of the diffractive a_1 resonance production. Nevertheless, we found that it is possible to replace this resonance by $\pi\rho$ in the unnatural parity 1^+S state, because it forms a narrow peak in the 3π invariant mass distribution, so can be treated as an effective pole, named a, in the dispersion relation for the axial current.

Presence of such an effective pole in the dispersion relation for the axial current allows to determine the a-nucleon coupling using PCAC, which relates the contributions of heavy states (saturated by the a pole and the pion pole). Additional information about the leptonic decay constant of a is obtained from the second Weinberg sum rule.

Although the $\pi\rho$ exchange corresponds to a Regge cut, rather than a pole, we found its Regge intercept to be rather close to the one for a_1 Reggeon, so the phase shift is similar as well.

Finally, we calculated the single transverse-spin asymmetry at different values of the kinematic variables, s, q_T and z, and found very good agreement with data.

* * *

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