On the A-dependence of the neutron single-spin asymmetry in pA-collisions

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Abstract.   Preliminary results of the PHENIX experiment on the single-spin asymmetry (A_N) for a neutron production in proton-nucleus collisions are discussed. The asymmetry A_N changes its sign and increases three-fold as the transition from p + p to p + Au interactions occurs. We call this phenomena "anomalous A-dependence of A_N". This unusual behavior is explained in the framework of the chromomagnetic polarization of quarks (CPQ) model. Dependence of A_N on centrality of collisions and the "ridge" effect in heavy ions collisions are discussed.

1. Introduction

Recently, the PHENIX experiment reported about the observation of an anomalous A_N dependence on the atomic weight A of the target [1]. The data are measured in the p+p, p+Al and p+Au collisions at 200 GeV in the c.m. frame. Neutrons are produced in the fragmentation region of polarized protons at a small transverse momentum: $p_T \approx 0.108$ GeV/c, $x_F \approx 0.54$ (see Fig. 1). The data [1] (solid points) and the CPQ model [2] predictions of $A_N(A)$ for the inclusive
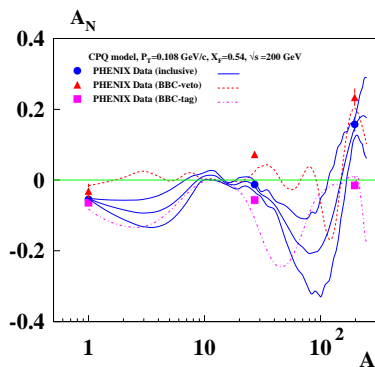
Figure 1. The $A_N(A)$ data [1] for the reaction $p^\uparrow + p(A) \to n + X$ and the CPQ model calculations.
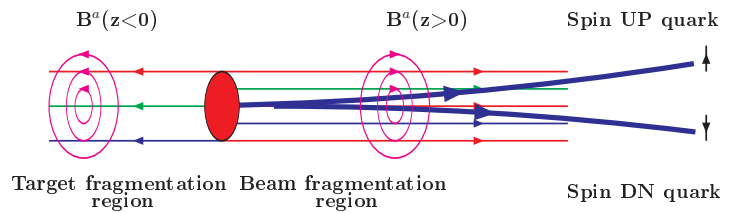
Figure 2. Chromo-magnetic polarization of quarks model (microscopic Stern-Gerlach apparatus). The circular transverse chromomagnetic field $\mathbf{B^a}$ is created by the relativistic moving spectator quarks and antiquarks. The probe quark gets an additional p_T kick to the left (right) when its spin is directed upwards (down). In general, the field direction and its value are different for the beam and target fragmentation regions.

trigger (solid curve) are shown in Fig. 1. Thin lines show estimates of one standard deviation for the CPQ model calculations. When the trigger prohibits any signal in the beam-beam counters

(BBC-veto trigger), the values of $A_N(A)$ are shifted upwards (triangles in Fig. 1). The signal requirement in the BBC counters (BBC-tag trigger) shifts $A_N(A)$ down (squares in Fig. 1).

## 2. Chromo-magnetic polarization of quarks model

A longitudinal chromoelectric field $\mathbf{E^a}$ and a circular transverse chromomagnetic field $\mathbf{B^a}$ are generated in the interaction region. Single-spin asymmetry is due to an additional p_T kick, caused by the Stern-Gerlach force that is acting on the quark dipole color moment in the inhomogeneous transverse circular chromomagnetic field (see Fig. 2). The precession of the quark spin in the chromomagnetic field changes the Stern-Gerlach force and leads to an oscillation of A_N as a function of its arguments in the case of a high $\mathbf{B^a}$ value. The asymmetry A_N is given by

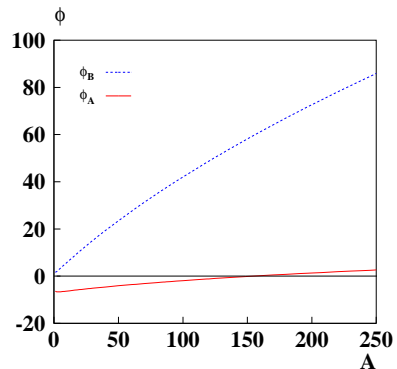$$A_N = C(\sqrt{s})F(p_T, A)[G(\phi_A) - \sigma G(\phi_B)], \tag{1}$$

where the function $G(\phi)$ takes into account the quark spin precession and is given by

$$G(\phi) = (1 - \cos\phi)/\phi + \epsilon \cdot \phi. \tag{2}$$

The quark spin precesses in the color field, as is described by the FT-BMT equation [3], updated for the case of chromomagnetic field and color quarks [2]. The parameter $\epsilon = -0.00497 \pm 0.00009$
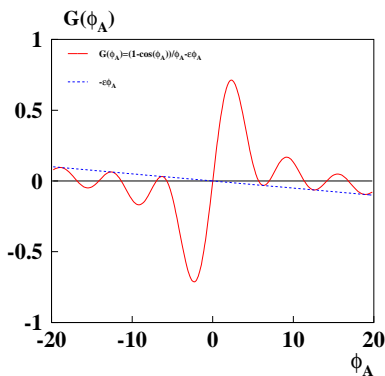
Figure 3. The function $G(\phi_A)$ in (1) and the linear term $-\epsilon\phi_A$.

Figure 4. The dependence of ϕ_A and ϕ_B on A.

in (2) and the other phenomenological parameters are determined from the global fit of the polarization data for the 81 inclusive reactions with 3465 data points [2, 4].

The main role in the origin of the anomalous A-dependence of A_N for the neutron production by polarized protons plays the term $[G(\phi_A) - \sigma G(\phi_B)]$ in (1), where $\sigma = 0.178$, ϕ_A and ϕ_B are the "integral angles of quark spin-precession" in the fragmentation regions of a projectile A and target B, respectively. The function $G(\phi_A)$, shown in Fig. 3, is an antisymmetric oscillating function of ϕ_A. The function $G(\phi_A)$ has the minimum at $\phi_A \approx -2.3$ and the maximum at $\phi_A \approx 2.3$. The peaks of $G(\phi_A)$ transform into the corresponding extrema of A_N, as a function of A. The spin-precession angles ϕ_A and ϕ_B for the inclusive reaction $p^{\uparrow} + p(A) \rightarrow n + X$ depend on the target atomic mass A, as is shown in Fig. 4. In particular, $\phi_A \approx -2.3$ at A=86 and $\phi_A \approx 2.3$ at A=215, where the corresponding extrema of $A_N(A)$ are expected.

The contribution (relative weight) ν of spectator quark or antiquark to the effective color field is determined by the color factors: $\nu(qq) \equiv \lambda = -0.1363 \pm 0.0003$ and $\nu(q\bar{q}) = 1$ [2, 4, 5]. It was found that for the qq-pair the antitriplet color state is dominant and for the case of the $q\bar{q}$-pair the singlet color state dominates in the two quark interactions. One of the quarks in the pair above is a spectator and the other is an active probe quark from the detected neutron.

The contributions of spectator quarks and antiquarks to the effective color field, in the fragmentation regions of colliding particles A and B (ν_A and ν_B) are given by

$$\nu_A = 1 + \lambda - 3B_{eff}\tau\lambda, \tag{3}$$

$$\nu_B = 1 + \lambda + 3(B_{eff} - 1)\lambda - 3\tau\lambda, \tag{4}$$

where B_{eff} is the effective number of nucleons in target nuclei, where $\tau = 0.0267 \pm 0.0005$. The spin-precession angles ϕ_A and ϕ_B are proportional to ν_A and ν_B, respectively. In the CPQ model, the effective number of nucleons, participating in the creation of a color field in $p + A_2$ collisions, is given by

$$B_{eff} = A_2(1 - (1 - (A_b/A_2)^{2/3})^{3/2}, \tag{5}$$

where

$$A_b = A_0 + (A_2 - A_0)exp(-W_0/(f_a\sqrt{s}))exp[-(p_T/p_m)^{a_f}], \tag{6}$$

where $f_a = A_2^{1/6}$, $A_2 \equiv A$ - the target atomic mass [2]. The transverse radius of the field $\mathbf{B^a}$ is $R_b \approx 1.2A_b^{1/3}$ fm. The CPQ model parameters are: $A_0 = 0.3084 \pm 0.0012$, $W_0 = 275.6 \pm 1.3$ GeV, $p_m = 0.152 \pm 0.038$ GeV/c, and $a_f = 3.09 \pm 0.05$. For large $\sqrt{s} > W_0/f_a$ and small $p_T \leq p_m$, the second term in (6) dominates, $A_b \approx A$, and the anomalous A-dependence of A_N is expected. At small $p_T \leq p_m$, all nucleons in the target nuclei are a source of spectator quarks due to the uncertainty relation principle. These additional spectator quarks increase the effective color field and cause the anomalous behaviour of $A_N(A)$.
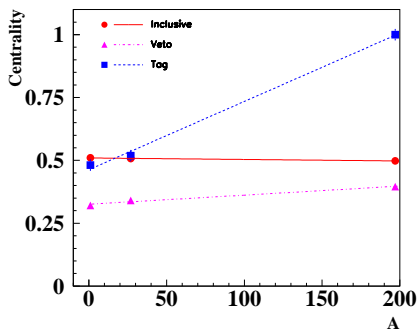
**Figure 5.** The A-dependence of centrality for the inclusive, BBC-veto and BBC-tag triggers.
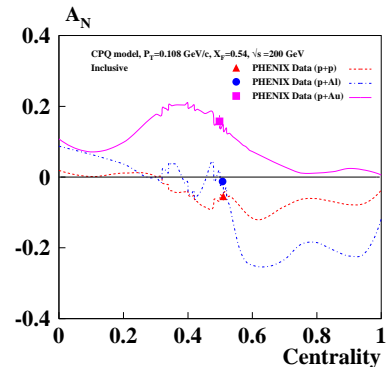
Figure 6. The dependence of A_N on the collision centrality for the p+p, p+Al and p+Au collisions.

3. Comparison of the $\mathbf{A_N(A)}$ data and the CPQ model calculations

The results of the $A_N(A)$ measurements [1] and the CPQ model predictions are shown in Fig. 1 for the three types of triggers. For the inclusive trigger, the data are well reproduced using the CPQ model and, in addition, two minima are predicted at A=3 and A=86, respectively. The letter correspons to the main minimum of $G(\phi_A)$ in (1). The large positive A_N on the Au target is due to the main maximum of $G(\phi_A)$ at A=215. In the case of not inclusive triggers, the selected samples have centrality of collision that differs from the mean value (0.5 for the inclusive one). The A-dependence of centrality is shown in Fig. 5 for the three types of triggers, disscussed above. For the inclusive trigger, the centrality is close to 0.5, as expected. For the BBC-veto trigger, the centrality of collisions is much less than 0.5 and since in this case the color

field is stronger, the asymmetry A_N is shifted upwards. The BBC-tag trigger selects centrality that is close to 1 for A=215 and corresponds to a very peripheral collisions. The color field is much weaker for peripheral collisions due to a smaller number of spectator quarks produced in the target fragmentation. As a result, the asymmetry A_N is shifted downwards for large A.

The dependence of A_N on centrality is shown in Fig. 6 for the cases of p+p, p+Al and p+Au collisions. As is seen in Fig. 6, the asymmetry $A_N(A)$ has a strong dependence on centrality for the Au target that explains the observed trigger dependence of A_N.
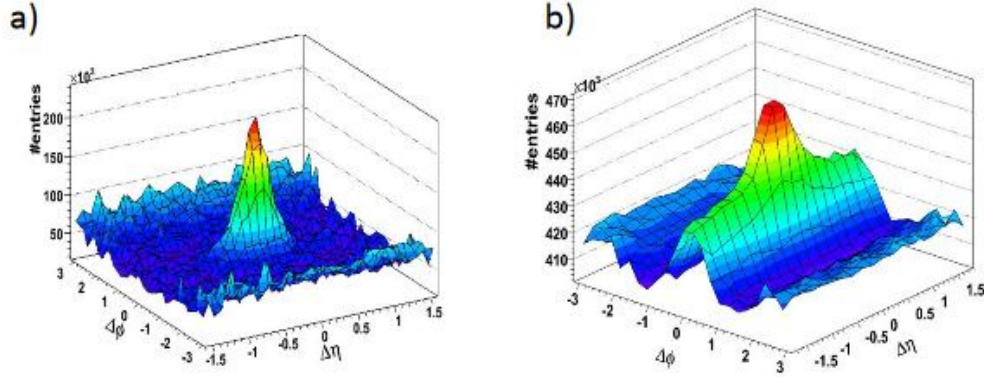
Figure 7. The two particle correlation function for the d+Au (left) and Au+Au (right) central collisions at $\sqrt{s} = 200$ GeV measured by the STAR experiment [6].

4. The origin of the "ridge" effect in the framework of the CPQ model

To evaluate the dependence of the chromomagnetic field on centrality, the so called "ridge" effect in heavy ions collisions [6] was analyzed in the framework of the CPQ model. The "ridge" phenomenon means the long-range correlations of two produced hadrons that depend on difference of their pseudorapidities ($\Delta\eta$). Pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$, where θ - polar angle. The difference in pseudorapidities of two hadrons is larger, on average, for more central collisions. At the same time, the difference in azimuthal angles ($\Delta\phi$) of two hadrons is narrow and has no strong dependence on centrality. In Fig. 7 is shown an example of the "ridge" structure measured in the STAR experiment [6]. For the central Au+Au collisions the width of the peak in the $\Delta\eta$ direction is much larger than along the $\Delta\phi$ axes.
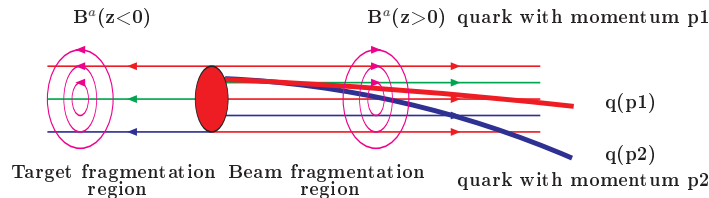

Figure 8. Schematic view of the interaction region as a microscopic color-magnetic lens, smearing a jet of quarks and antiquarks in a radial direction due to the Lorentz force.

This behavior is explained in the CPQ model as a result of the Lorentz force acting on a color charge in a circular transverse chromomagnetic field. In the CPQ model the interaction region can be considered as a microscopic color-magnetic lens, shown schematically in Fig. 8. The polar angle of each probe quark changes after passing through the field and the width $\Delta\eta$ of the difference in the pseudorapidity of the two quarks increases, in agreement with the data

behavior. The width of azimuth angle difference $\Delta\phi$ does not change significantly due the fact that the Lorentz force is directed radially to (or from) the center of the collision zone. The "ridge" effect should decrease when the momentum (or p_T) increases, in accordance with the data. Additional contribution to $\Delta\eta$ comes from the difference of Lorentz force for the quark and antiquark (which have opposite color charges). The dependence of the effective chromomagnetic field B^a, normalized to its value for the inclusive trigger, on the centrality u_c is found as follows:

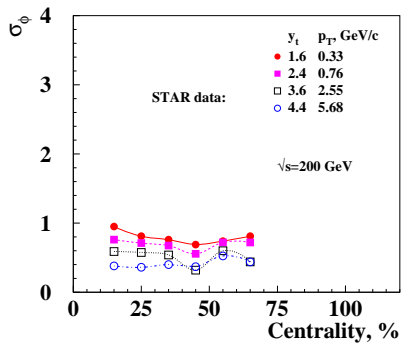$$U(u_c) = B^a(u_c)/B^a(0.5) = c_1 - c_2(u_c + u_c^2) + c_3(u_c^3 + u_c^4 - u_c^5), \qquad (7)$$

where c1 = 6.1184, c2 = 9.5397, c3 = 13.0326, and $0 < u_c < 1$ is the centrality of collisions.
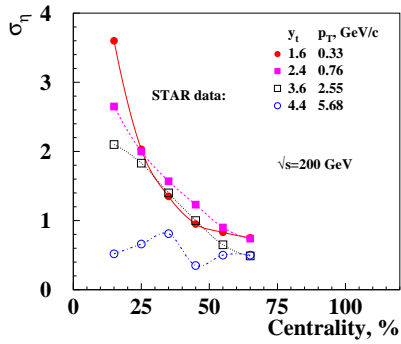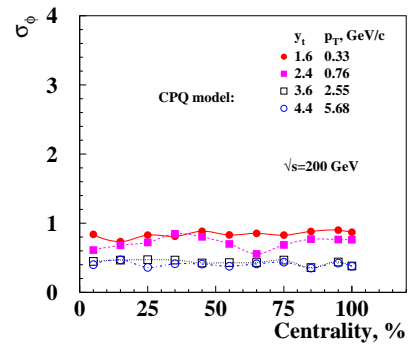

Figure 9. The dependence of σ_η on centrality. The STAR data are measured at $\sqrt{s} = 200$ GeV [7].
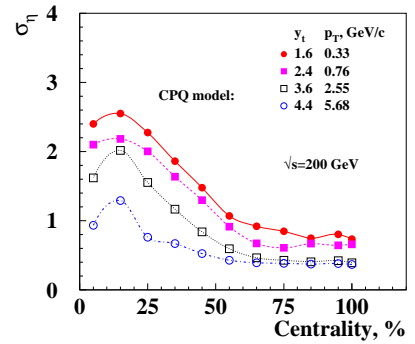
Figure 10. The dependence of σ_η on centrality. The CPQ model calculations are at $\sqrt{s} = 200$ GeV.


**Figure 11.** The dependence of σ_ϕ on centrality. The STAR data are measured at $\sqrt{s} = 200$ GeV [7].

Figure 12. The dependence of σ_ϕ on centrality. The CPQ model calculations are at $\sqrt{s} = 200$ GeV.

To compare the "ridge" data and the CPQ model calculations the projections of two particle correlations on $\Delta\eta$ and $\Delta\phi$ axis were fitted by the Gaussian distribution. The dependence of the fit parameter σ_η on centrality for the data at $\sqrt{s} = 200$ GeV [7] is shown in Fig. 9. The width of the peak (σ_η) is decreasing with the rise of centrality value and p_T of hadrons. This behavior is consistent with the model predictions, shown in Fig. 10. In Figs. 11 and 12 are shown the data [7] and the model estimates for the parameter σ_ϕ, as a function of centrality. There is no significant dependence of σ_ϕ on centrality but the dependence on p_T is still essential.
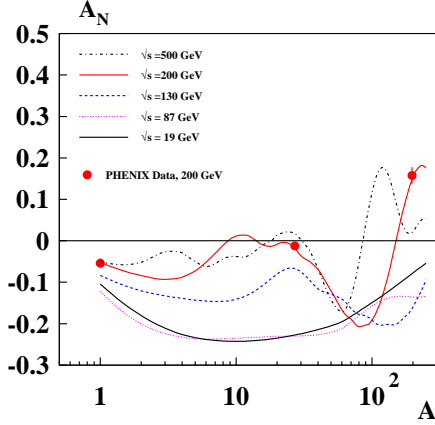
Figure 13. The dependence of A_N on A for $p_T = 0.108$ GeV/c, $x_F = 0.54$, and the inclusive trigger.
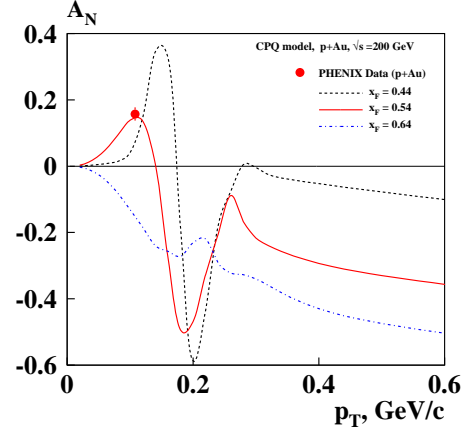
Figure 14. The dependence of A_N on p_T for $\sqrt{s} = 200$ GeV, Au target, and a few values of $x_F - 0.44$, 0.54, and 0.64.

5. Calculations of $\mathbf{A_N(A)}$ and $\mathbf{A_N(p_T)}$

The data [1] and calculations of $A_N(A)$ for different energies are shown in Fig. 13. The positions of maxima and minima of $A_N(A)$ are moving to lower A values with the rise of energy. For $\sqrt{s} \leq 100$ GeV the sign of $A_N(A)$ is negative for all values of A. The dependences of A_N on p_T for $\sqrt{s} = 200$ GeV, Au target, and $x_F = 0.44$, 0.54 or 0.64 are shown in Fig. 14. The oscillating shape of $A_N(p_T)$ is due to the quark spin precession in the effective chromomagnetic field.

Conclusions and outlook

1) The anomalous A_N dependence on A for the production of neutrons in pA-collisions is due to the Stern-Gerlach force action and the quark spin-precession in the effective chromomagnetic field. This is expected for $p_T \leq 0.3$ GeV/c, $x_F = 0.6$ and $\sqrt{s} \geq 100$ GeV.

2) The model of chromo-magnetic polarization of quarks predicts not only a large positive peak in the $A_N(A)$ dependence at $A \approx 215$ but also negative peaks at A=3 and A=86.

3) The dependence of $A_N(A)$ on the trigger type can be caused by the dependence of the color field on the collision centrality.

4) The "ridge" effect in the two hadron correlations that was observed in the heavy ions collisions can be explained in the framework of the CPQ model.

5) A similar anomalous A-dependence of $A_N(A)$ can exist for the other inclusive reactions at low $p_T \leq 0.3$ GeV/c. This can be tested in the experiments at IHEP, JINR and BNL.

References

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