THE STAR SPIN PHYSICS PROGRAM

S.B. Nurushev
Institute for high energy physics
142280 *Protvino, Russia*
E-mail: nurushev@mx.ihep.su
(on behalf of the STAR collaboration)

Abstract

The STAR Collaboration aims to observe polarized proton collisions at RHIC to obtain information about the spin structure of the nucleon. The main emphasis is the determination of the degree that gluons contribute to the proton's spin from measurements of jet and direct photon productions for collisions at $\sqrt{s}$ = 200 and 500 GeV, when both protons are longitudinally polarized. In addition, the flavor decomposition of valence and sea quarks polarizations will be probed by production of W and Z bosons in the collisions of longitudinally polarized protons. The transversity structure function may be accessiable in collisions of transverselly polarized protons. Hyperon polarizations and the role of spin as a signature of the Quark-Gluon plasma are discussed too.

Introduction

The advent of the polarized RHIC marked a milestone in the study of the spin phenomena at high energies. For the first time the polarized proton beams of high quality were obtained. The impressive Spin Program was developed [1] which includes : a) the measurement of the gluon polarization, b) the separation of the flavor polarization, c) study of transversity, d) hyperon polarizations, e) study of the resonance polarization, etc. This talk presents briefly some of the STAR Spin Studies which were done or will be performed in coming years.

1. STAR Detector

The STAR detector was built for study the heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Later when the spin program was approved, the STAR Collaboration begun to upgrade the main detector to fit to the new challenges. This job still continues.

The STAR detector contains the following major elements:

- solenoidal magnet with field up to B = 0.5 T
- time projection chamber (TPC). The barrel TPC covers a full azimuthal angle and a pseudorapidity region $-1.5 \leq \eta \leq 1.5$
- barrel electromagnetic calorimeter. Acceptance: $-1 < \eta < 1$, $\Delta\varphi = 2\pi/5$ at time being
- endcup electromagnetic calorimeter. Acceptance: $1 < \eta < 2$, $\Delta\varphi = 2\pi$

- beam-beam counters (BBC). Acceptance : $2.4 < |\eta| < 5.0$, $\Delta\varphi = 2\pi$
- forward pion detector (FPD). Acceptance : $3.1 < \eta < 4.4$ + upgrade

A full description of the STAR elements are presented in paper [2]. Here we mostly indicated those detectors which produced the first spin physics results during the RHIC runs 2(2002) and 3(2003).

2. The polarized RHIC Complex

The polarized RHIC Complex includes the following parts:

- optically pumped polarized ion source (OPPIS). The polarized proton source furnishes I=o.5mA current,at polarization $P = 70\%$.
- linac accelerating polarized protons up to 200 MeV
- booster accelerating protons till 1.56 GeV/c
- alternating gradient synchrotron (AGS) accelerating protons up to 33 GeV/c
- two beam transport systems for injecting polarized protons into the blue (clockwise) and yellow(anticlockwise) rings. The injection momentum is around 23 GeV/c
- two superconducting rings groupping them in bunches (60 at moment, but later up to 120 bunches) and accelerating the injected polarized protons to the top energy 500 GeV

The polarized RHIC is equipped with four blocks of siberian snake magnets. Additionally eight spin rotators are used in order to get the longitudinally polarized proton beams at the 6 and 8 o'clock cross section regions for STAR and PHENIX detectors.

Polarimetry. For the measurements of the proton polarizations at the different stages of accelerations the relative and absolute polarimeters are foreseen. At the exit of the OPPIS the Lamb shift polarimeter is used. At the exit of the linac a standard carbon analyzer is used, while at the entrance of booster no polarimeter was foreseen. AGS had a carbon polarimeter in the first polarized beam run, but later a CNI polarimeter was added.
RHIC has several types of polarimeters. The first one was a general type installed close to the 12 o'clock region. This was absolute pC polarimeter based on the detection of the recoil carbon in the Coulomb-nuclear interference(CNI) region [3]. It was successfully used for the fast tune of the beam polarization in the case of ramp of RHIC energy. Earlier the decision was taken to replace pC polarimeter by pp polarimeter. The reasons are following:

- due to the higher mass recoil carbon has a much smaller kinetic energy than proton. As result in pC polarimeter it is impossible to reach the region of the maximum analyzing power
- in pC reaction a background is hihger than in pp scattering

- pp analyzing power is calculable with better confidence. Therefore its analyzing power is more reliable
- pp analyzing power may be quickly and absolutely calibrated. For that one can use the polarized hydrogen jet and unpolarized target in combination with unpolarized and polarized beams correspondingly. Since the polarization of the polarized proton jet target(PPJT) can be determined with high precision (about 5%) the analyzing power of pp reaction can also be determined on the same level of accuracy.

As was indicated some time ago [4] one needs to have in addition to the general polarimeter so called the local polarimeter. It should fulfill two functions. First to measure as quickly as possible the polarization of the beam at the point of interest. For example, at 6 o'clock interaction point (IP) for STAR. Secondly, it must be able to control the parasitic components of the beam polarization. For example, if STAR measures the longitudinal double spin asymmetries we should be confident that the beam has no transverse components of polarization. To reach these goals it was proposed to use the polarimeters on the base of the inclusive π^0 and photon productions [5], [6]. FPD measured the analyzing power of the π^0 at $\sqrt{s} = 200$ GeV and showed that the essential analyzing power exists at this energy as it was expected [7]. Therefore this reaction can serve as the local polarimeter for STAR.The measured by FPD analyzing power is close to one measured by E704 in the same reaction for $\sqrt{s} = 20$ GeV [8]. In detail the FPD results are presented in [9].

The next interesting results are relevant to the BBC measurement. The raw analyzing power of the charged particles measured by BBC appears to be on the same level of magnitude as it was measured by the general CNI pC polarimeter, that is, $A_N(BBC) = 0.1$ % with accuracy of 10% [9]. This result is not yet understood, but the real asymmetry was used for tuning the spin rotator at 6 o'clock IP. Therefore BBC may be used also as the fast local polarimeter by STAR.

As it was established earlier the inclusive neutron production at small p_T region shows also a significant analyzing power [10]. For STAR to be able to measure such neutron asymmetry detected in the polarized proton fragmentation region one needs to add the forward hadron calorimeter.

As conclusion one can state that a set of new polarimeters were discovered at the polarized RHIC during the first run and they may be used effectively as the local polarimeter.

Asymmetry measurements on the level of $\leq 10^{-3}$ become the realistic ones. Due to the high luminosity, the purity of the polarized beam and "polarized target" (in contrast to the fixed target (FT) experiments) the inclusive reactions can be studied up to large transverse momenta, where one can apply the pQCD calculations. Additionally taking into account the very rapid rotations of the beam polarization one can avoid the systematic errors and make possible measurements of the tiny spin effects (on the level of 10^{-3} and less). Evidently the disentangling of the gluon polarization and decomposition of the quark and anti-quark polarization become possible due to the large acceptance of the STAR detector. It is obvious also that the large of the center of mass(c.m.) energy becomes the essential factor in fulfilling the Star Spin Physics Program(SSPP). In the following we describe the main features of the polarized RHIC and STAR detector, briefly outline the importance of the first two polarized beam runs. Then we present the main SSPP making emphasis on the abilities of detectors to reach our goal.

Table 1: **Features of the E-704 and polarized RHIC experiments**

Parameters	E-704	RHIC
c.m. energy, GeV	19.4	500
Average beam polarization, %	45 ± 8	70 ± 3.5
Frequency of polarization reversal, Hz	$1.4 \cdot 10^{-3}$	$5 \cdot 10^{6}$
Beam size, mm	10	0.4
PPT, 20cm, pentanol; P_T, %	80	–
Pol.p/cm2	9.8×10^{23}	–
Dilution factor, D	≈ 10	–
1m LHT, p/cm^2	$4.2 \cdot 10^{24}$	–
Pol. Beam lum., $L^{B0}, cm^{-2}s^{-1}$	$2 \cdot 10^{29}$	–
Pol. Targ. lum., $L^{0T}, cm^{-2}s^{-1}$	$5 \cdot 10^{28}$	–
RHIC lum., L, $cm^{-2}s^{-1}$	–	$2 \cdot 10^{32}$

In order to get some ideas about the quality of the polarized RHIC we must compare it to other similar facility. The one closer in energy to RHIC is the well known Fermilab polarized beam facility. The figure of merits for the different parameters are presented in the following Table 1.

In Table 1 we present only the polarized proton beam though the E704/581 produced also polarized antiproton beam. For RHIC the top energy was taken which is not yet reached at time being. The advantages of the polarized RHIC are illustrated in the following points:

- luminosity. The highest luminosity in E704 was reached for the single spin asymmetry (SSA) measurement. As can be seen in Table 1 the RHIC luminosity will be by 3 order of magnitude higher.
- polarization. The RHIC beam polarization is higher by a factor of 1.5 than in E704 case. As was stated earlier the accuracy of the polarization measurement will be much better at RHIC.
- spin reversal. This technic is important for elimination systematic errors. Frequency of the polarization reversal is much higher at RHIC.

As one can conclude the polarized RHIC opens a new epoch in study of spin effects.

3. The first polarized beam runs at $\sqrt{s} = 200$ GeV

1. **BBC detector**. It revealed the raw asymmetry of the charged particles on the level of $A_N = (1 \pm 0.2) \cdot 10^{-3}$ for each run. This value is comparable to the raw CNI asymmetry $A_N(CNI) \equiv (3 \pm 0.3) \cdot 10^{-3}$. This means that the BBC can be used as a relative local polarimeter. Due to a high quality of polarized beams the experiment becomes able to measure the asymmetry with a high precision for the first time. The BBC measured asymmetry is not yet understood. The direct way of separation effects from the positively

and negatively charged particles might be to build the forward arm magnetic spectrometer expanding the ability of STAR to make measurements in the beam fragmentation region.
2. **TPC**. The measured raw asymmetry of the leading charged particles (LCP) is close to zero on the level of $A_N = (1 \pm 1) \cdot 10^{-2}$ up to $p_T \approx 4$ GeV/c.This result is important for several reasons. Firstly, E-704 measured only π^0 inclusive asymmetry (which was also consistent with zero) at midrapidity region [8], but not the charged pions asymmetry. Therefore TPC result is the first one. Secondly since the LCP asymmetries are zero for both types of charged particles one can expect that $A_N(\pi^0)$ will be also zero. Thirdly, there is very important hanging problem. For the first time It was shown by A. Efremov, that the quark polarization at large transverse momentum can be written as follows

$$P_c = \frac{\kappa_1(\Delta)}{\kappa_2(\Delta)} \frac{2m_c c_\perp}{c_\perp^2 + m_c^2} \tag{1}$$

Here $c_\perp$ is the quark transverse momentum, κ_1 and κ_2 are functions of pseudorapidity Δ. Similar expression was obtained in paper [12]. In the expression for quark polarization (asymmetry) calculated by pQCD there is a mass factor m_c. There are two approaches to this factor. In one case [12], it was stated that this mass must be a mass of the current quark($\approx 10MeV$). In this case asymmetry will be very small and unmeasurable at present state of art. In second case [13] it was stated that the mass should be equal to the mass, M, of the polarized hadron participating in reaction, that is, to the proton mass ($\approx 1GeV$). For midrapidity region the authors of paper [13] gave the approximating formula for the inclusive pion asymmetry

$$A_N \approx \frac{\alpha_s(p_T^2) M p_T}{30 m_T^2}, \tag{2}$$

where $m_T^2 = m_\pi^2 + p_T^2$, p_T is the transverse momentum of pions. The numerical estimate in this case leads to the asymmetry of pions of order 3% for $p_T \approx 1$ GeV/c. STAR has a chance to solve this important problem. For that one needs to improve the statistics and show that the asymmetry is either nonzero on the level of 1% or much less than 1%. This will be an important achiement.
3.**FPD**. It revealed a large analyzing power in π^0 inclusive production in the beam fragmentation region at $\sqrt{s} = 200$ GeV (see L. Bland presentation in this proceedings). This asymmetry was predicted by different quark models but the calculations are tedious and not transparent for experimentalists. X. Artru stated in discussion during my presentation that the similarity of the $A_N(\pi^0)$ at $\sqrt{s} = 20$ and 200 GeV is natural in the model of limiting fragmentation. A simple model was proposed by Ryskin [14] which is also able to predict the analyzing power if the differential cross section of process is known. Therefore FPD data must be improved in order to be able to select a right model.

4. Main goals of the STAR Spin Program

The STAR collaboration long ago formulated the main spin program at RHIC [1]. It includes the following items:

• **Gluon polarization**. It is known that DIS can not directly furnish informations on the gluon polarization. The accumulated up to now experimental data show that several questions about the parton spin distributions are not yet answered (see Fig.1).

For example, the spin of nucleon consists of three parts - quark polarization, Σ, gluon polarization, ΔG, and the orbital momentum of quarks and gluons. DIS experiments determined only Σ, which contributes only 1/3 to the nucleon spin. Moreover as it is seen from Fig.1 contributions of the valence and sea quarks are not separated.

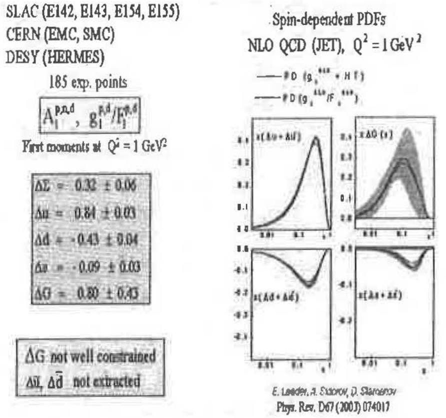

Figure 1: The global fit to the data of the DIS experiments measuring the parton distribution functions.

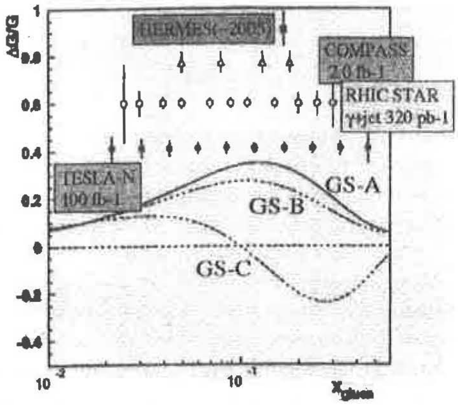

Figure 2: The expected results of the gluon polarization measurements by the different experiments over the world.

The gluon polarization is known only poorly from scaling violation. The third term is never measured. STAR may determine the gluon polarization through double spin asymmetry, A_{LL}, measurements in the reactions: a) $p+p \to direct\ photon + jet + X$, b) $p+p \to jet + jet + X$, c) $p+p \to direct\ photon + X$, d) $p+p \to jet + X$. The first two reactions are preferable for reconstruction of the parton kinematics.
For reaction a) the estimates were done at $\sqrt{s} = 200$ GeV, $L = 320\ pb^{-1}$ integrated luminosity, beam polarization $P_B = 70\%$. The results show that the region $0.01 \le x_g \le 0.3$ may be covered. Over this interval of measurements the ratio $\Delta G/G$ can be determined with a precision of order ≈ 0.05 which will be much better than the accuracy reached by SMC experiment ($\Delta G/G = -0.3 \pm 0.30(stat) \pm 0.11(syst)$, see talk at this Workshop by K. Kowalik). Result of such estimates is presented in Fig.2 together with the expected data from the experiments HERA-B, HERMES, COMPASS and TESLA. It is seen from this Fig.2 that the STAR data will be gathered over the wide x_g region(0.01-0.3) and will reach the high precisions.

• **Quark/antiquark polarization and flavor decomposition**. This task will be solved by using the parity violating reaction $p + p \to W^{\pm} + X$. One of the proton beam must be longitudinally polarized. The asymmetry is defined in the following way

$$A_L(W^+) = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}, \tag{3}$$

$$A_L(W^-) = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}. \tag{4}$$

These equations in the extreme case lead to the following relations:

When $x_1 \gg x_2$ one gets

$$A_L(W^+) \to \frac{\Delta u(x_1)}{u(x_1)}, A_L(W^-) \to \frac{\Delta d(x_1)}{d(x_1)}. \tag{5}$$

When $x_1 \ll x_2$ one gets

$$A_L(W^+) \to -\frac{\Delta \bar{d}(x_1)}{\bar{d}(x_1)}, \quad A_L(W^-) \to -\frac{\Delta \bar{u}(x_1)}{\bar{u}(x_1)}. \tag{6}$$

The indicated above four measurements will allow to disentangle the flavor dependence of the parton polarization. In such measurements the addition of the endcap EMC becomes essential allowing to enlarge the pseudorapidity region. The measurements of the asymmetries for jet productions with longitudinally polarized proton beams will give a hint into the problem of the parity violations. Due to the large yields the parity violating asymmetries might be searched for pion productions at STAR. Moreover as it was demonstrated by BBC such asymmetry may be already measured on the level $10^{-3} \div 10^{-4}$ as we discussed earlier. This will be already an important achievement.

• **Transversity and the transverse spin effects.** The transverse spin distributions of partons in the transversally polarized protons will be studied through several processes. First of all this is a single transverse spin asymmetry. The first result on this subject was obtained by FPD apparatus. It will be updated and continue the data taking. The interesting and promising method is the jet production. Application of the handedness method to this reaction may give information on the final quark transverse polarization. The main problem here may be the analyzing power of the quark disintegration into three charged particles(minimum number of particles needed for analysis). There are possibilities to use the dijet or Drell-Yan pair productions. All these channels can be studied at STAR.

• **Hyperon polarization.** The easy measurements and important at the same time are the single spin asymmetry in inclusive Λ production and the polarization of the Λ. The equality $A_N(\Lambda) = P(\Lambda)$ is very crucial for testing the theoretical models. Beyond the 3 observables for Λ, namely, differential cross section, polarization, P, and asymmetry A_N there are five spin transfer parameters (in Wolfenstein classification: D_{NN}, R, R', A, A') and 6 spin correlation parameters. Their measurements will allow to reconstruct the parton distribution and fragmentation functions. One of the spin transfer parameter, when the longitudinally polarized proton beam may transfer spin to the longitudinal component of the final Λ was proposed in paper [15].This parameter, A', is sensitive to the flavor spin transfer and can be measured at STAR with accuracy of several percent in the pseudorapidity region $-2 < \eta < 2$. In this calculation the low limit was taken for the Λ transverse momentum ($p_T > 12$ GeV/c).

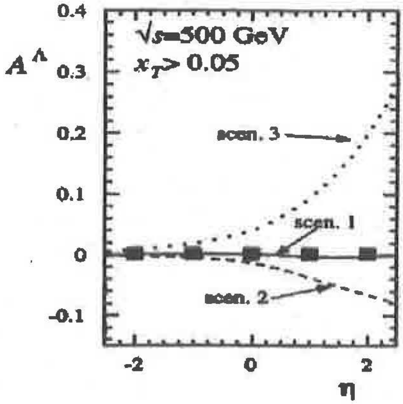

Figure 3: The expected asymmetry A'=A^Λ as a function of the Λ pseudorapidit for the various sets of spin dependent fragmentation functions discussed in the main text.

The results are presented in Fig.3. The curve 1 corresponds to the case when the fragmentation function is due to only strange quark. The curve 2 assumes that all three quarks building the Λ hyperon contribute to the fragmentation process. And finally the curve 3 reflects the case when all fragmentation functions are supposed to be equal. It is concluded that STAR will be able to distinguish between these three scenarios.

5. Spin as a probe of the Quark-Gluon Plasma

In papers [16, 17, 18] this problem was discussed. In paper [16] three items were analyzed.

1. **Lepton pair production**. Without QGP formation the angular asymmetry of kind $1+cos^2\theta$ should exist, where θ is an emission angle of lepton in the plasma c.m.s., while in the case of formation of QGP this distribution becomes isotropic.

2. **Hyperon polarization**. It is well known that Λ is polarized in pp-interaction up to top ISR energy 63 GeV. Suppose it stays polarized in pp interactions at RHIC energies too. Then if the QGP is produced the Λ polarization should disappear, since there is no preferred normal in the plasma rest frame. So measuring polarization in pp and Au-Au collisions one can search for the moment of the QGP formation.

3. **Resonance production**. The resonance polarization should be zero if they are produced in the plasma rest frame.

All indicated above reactions can be measured at star. In paper [17] $\bar{\Xi}$ production and decay were analyzed. It is well known that the abundant $\bar{\Xi}$ production is expected in the case of the QGP formation. This fact can be revealed directly. But the same fact might be established by independent method-measuring the longitudinal polarization of the $\bar{\Lambda}$ coming out from the $\bar{\Xi}$ decay. This might be useful as an additional support of the production of the QGP. In paper [18] the attention is attracted to the measurements of the hyperon polarization in comparative way- for pp interactions and for heavy ions (example, Au+Au) interactions. If the polarization exists in the first case and absent in the second case this may indicate on new state of nuclear matter in nuclear interactions.

Summary

The single and double spin asymmetries were measured by TPC for inclusively produced charged particles. Though the asymmetries are consistent with zero with error bar around $1\div2\%$ further improvements in precisions may allow to solve the problem of mass (quark or hadron) in the famous pQCD formula for quark polarization(asymmetry). The analyzing power in order of 10^{-3} (raw asymmetry) was revealed by BBC. This result is very crucial since allow to use BBC as a fast local polarimeter. Significant single-spin asymmetry was found by FPD in the inclusive π^0 production at $\sqrt{s} = 200GeV$ in the polarized beam fragmentation region. STAR at RHIC aims to start a new generation of proton spin structure studies including gluon polarization, spin/flavor decomposition of the valence and sea quarks, transversity and hyperon polarizations. Further extension of the STAR Spin Program is under development.

I would like to thank L. Bland, V. Mochalov and M. Tokarev for valuable discussion and help during preparation of this presentation.

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Discussion

Q. (E.Bubelev, JINR, Dubna): Is there a possibility at RHIC to measure multiparticle events to reconstruct resonances and to investigate there spin features?

A. Yes, this possibility realized at RHIC by Bland Leslie (BNL, USA) for example.

Comment. (Bubelev, JINR, Dubna): This reaction and investigation should be done in the Lobachevsky velocity space (LVS) patterns for multiparticle reactions, because LVS is a unique mathematical tool which is entirely adequate to high energy particle physics. So that all symmetries as already known and are conserved in the LVS. I reported 19 September at Round Table about an absolute spin alignment in the LVS for light vector mesons $\rho, \omega, ...$ as an example of solving small part of general Fundamental Inverse Scattering Problem refereed to spin features of light vector mesons.

Q. (X.Artru, Institute de Physique Nucleaire, Lyon): According to the Limiting Fragmentation Hypotheses (postulated 40 years ago and experimentally well verified), each inclusive spectrum does not depend on s, at fixed p_T and x_F. So, it is not surprising that the single spin asymmetry for inclusive π^0 at $x_F = 0.5$ does not decrease between E704 and STAR energies.

A. We should give an explanation through the ratio of $R = |f_{+-}|\sin(\varphi)/|f_{nsf}|$ in asymptotic energy region