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Comparative study of the inclusive asymmetries induced by polarized protons and antiprotons at 16 GeV/c at the U–70 accelerator

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Abstract. The only comparative study of the inclusive pion single-spin asymmetries produced in the interactions of the polarized protons and antiprotons in collisions with unpolarized proton was carried out at E–704 experiment. Significant asymmetries were found at large $x_F$ and middle $p_T$, $\pi^+$ and $\pi^0$ asymmetries have positive signs while $\pi^-$ has negative one in the $p^+ + p$ collisions, while in the $p^- + p$ interactions the $\pi^-$ and $\pi^0$ asymmetries have positive signs while $\pi^+$ has negative sign. Similar experimental study can be done in the SPASCHARM experiment at U–70 accelerator at IHEP for various secondary particles with the use of 16 GeV polarized proton and antiproton beams.

1. Introduction

Inclusive reactions measured with polarized (anti)proton beam give insight into the spin dependence of the underlying partonic processes and add new input regarding the problem of the spin structure of polarized protons. Significant polarization effects appear already at relatively low values of the transverse momentum $p_T$ ($p_T \sim 1.0$ GeV/c), where perturbative quantum chromodynamics (pQCD) is not expected to be applicable. Therefore the new experimental measurements with high statistics as well as phenomenological studies are essential for future progress in quantitative description of spin observables.

The following inclusive reactions are used for study of single-spin asymmetries for pions

$$p^+ + p \to \pi^\pm + X,$$  \hspace{1cm} (1)

$$\bar{p}^- + p \to \pi^\pm + X.$$  \hspace{1cm} (2)
The analyzing power $A_N$ is the physics observable under consideration here. The $A_N$ is deduced from the measured yields of pions produced in a well defined azimuthal angular interval around the beam axis using vertically polarized $p$ ($\bar{p}$) of both polarization signs:

$$A_N(z) = \frac{1}{P_B(\cos \phi)} \frac{N_\uparrow(z, \phi) - N_\downarrow(z, \phi)}{N_\uparrow(z, \phi) + N_\downarrow(z, \phi)}.$$  

Here $z \equiv (p_T, x_F, \sqrt{s})$ – a set of kinematic variables, $p_T$ is the pion transverse momentum, $x_F = 2p_L/\sqrt{s}$. Feynman variable for pion with longitudinal momentum $p_L$ at the collision energy $\sqrt{s}$, $P_B$ is the beam polarization, and $\phi$ is the azimuthal angle between the beam polarization axis directed upward and the normal to the production plane. $N_\uparrow$ ($N_\downarrow$) is the number of pions produced for positive (negative) spin orientation of the beam (anti)protons at the target, normalized to the corresponding beam flux. The reactions (1) and (2) were studied at $p = 200$ GeV/$c$ ($\sqrt{s} = 19.4$ GeV) with the E–704 setup [1] and here it is suggested to continue such a study in deeply non-perturbative region at $p = 16$ GeV/$c$ ($\sqrt{s} = 5.64$ GeV) in the SPASCHARM project [2, 3, 4].

### 2. The E–704 results for secondary pions

The magnitude of $A_N$ increases for both $\pi^+$ and $\pi^-$ particles with $x_F$ for $p^+$ beam, but the sign of $A_N$ is negative for the $\pi^-$ data. The values of $A_N$ are large for high values of $x_F$, up to $0.29 \pm 0.09$ for $\pi^+$ and down to $0.37 \pm 0.07$ for $\pi^-$. Detailed analysis of data at $p = 200$ GeV/$c$ shows a threshold effect in which $A_N$ increases dramatically above $p_T = 0.7$ GeV/$c$ [1].

The E–704 experimental results obtained for $A_N(x_F)$ above and below $p_T$ threshold indicated that the increase of $A_N$ is primarily $x_F$ effect above a $p_T$ threshold. The situation is similar for study of the $A_N(x_F)$ with $\bar{p}^+$ beam with taken into account the change of signs of electric charge for the beam and secondary particles under consideration. Furthermore the $p_T$ dependence was obtained for $A_N$ for charged pion production in inclusive reaction (2) with $\bar{p}^+$ beam [5]. As example, figure 1 shows the dependence of $A_N$ on $x_F$ (left) and $p_T$ (right) for secondary charged pions in (2). In this case the E–704 data exhibit an almost mirror symmetric dependence in $x_F$. The analyzing power for $\pi^-$ production increases from 0.0 to about $+0.25$ with increasing $x_F$ above $p_T \sim 0.5$ GeV/$c$ while, for $\pi^+$ production, $A_N$ decreases from 0.0 to about $-0.35$ with increasing $x_F$ above the same $p_T$. The E–704 results with $\bar{p}^+$ show a threshold effect about $p_T \sim 0.5$ GeV/$c$, above which $A_N$ increases in magnitude for both $\pi^+$ and $\pi^-$ and for transverse momenta below this $p_T$ value, $A_N$ is significantly smaller and compatible with zero [5]. The threshold effect was also confirmed by the results of additional analysis for $p_T \geq 0.5$ GeV/$c$. Therefore the E–704 experimental results for (2) show the magnitude of $A_N$ increases for both types of charged pions with increasing $x_F$, but the sign of $A_N$ is positive for the $\pi^-$ data and negative for $\pi^+$ data above the same $p_T \sim 0.5$ GeV/$c$. It appears that $A_N$ depends primarily on $x_F$ namely, and reaches large values above the $p_T$ threshold of about 0.5 GeV/$c$ as well as for inclusive reaction (1) with charged pions at some higher threshold $p_T$.

Therefore $A_N$ seems similar (in the sense of behavior and magnitude) for $p^+ / \bar{p}^+$ beams in the case of opposite charges for pions, i.e. the reaction (1) with proton beam and inclusive $\pi^+$ the $A_N$ appears to be similar to that in reaction (2) with antiproton beam and inclusive $\pi^-$ and vice versa. One can note that the models based on non-perturbative approaches, such as a soft pion exchange mechanism [6], resonance-decay interference between real and virtual channels [7] and rotating constituents in the polarized (anti)proton [8] appear to be in good qualitative agreement with the features of the data on the pion production asymmetry measured with the both polarized protons and antiprotons.

The kinematic dependencies of $A_N$ on $x_F$, $p_T$ were also studied for the $\pi^0$ production in the inclusive reactions (1) and (2) in E–704 experiment [1, 9, 10, 11]. For the $\pi^0$ data obtained with
Figure 1. $A_N$ data for $\bar{p}^+\pi^-$ beam as a function of $x_F$ integrated over $p_T$ in the range $0.2 - 1.5$ GeV/c (left) and depends on $p_T$ in the $x_F$ range of $0.2 - 0.9$ (right) for charged pions. Experimental points for $\pi^-$ are shown by solid symbols, for $\pi^+$ by open ones. For clarity, first two $\pi^-$ ($\pi^+$) data points are slightly shifted on left (right) in each panel. Data are taken from [5].

$p^+$ beam, $A_N(x_F)$ has the same sign as for $\pi^+$ data and is about half as large [1, 10]. The similar situation is observed for $A_N(x_F)$ in the $\bar{p}^+ + p$ inclusive reaction for comparison $\pi^0$ results with $\pi^-$ analyzing power [5, 10]. Thus the $\pi^0$ productions by polarized $p^+$ and $\bar{p}^+$ are related by charge conjugation of the beam and the produced particle. The measured asymmetries have the same sign and similar $x_F$ dependence [10]. At large $x_F$, there is an indication that the magnitude of $A_N$ for $\pi^0$ production by incident antiprotons is less than for incident protons. This would mean that the interactions involve constituents other than gluons and quark-antiquark pairs in the target proton. The $A_N$ is observed to be zero for single-spin inclusive $\pi^0$ production in $p^+ + p$ and $\bar{p}^+ + p$ inclusive reactions in the $1 < p_T < 3$ GeV/c region within a statistical accuracy [11]. But it should be noted that in this case the amount of data for studying (2) interactions was an order of magnitude less than that for (1) interactions. In general in perturbative QCD single-spin transverse asymmetries are expected to be practically zero. Thus this expectation in the $1 < p_T < 3$ GeV/c region is confirmed by the data from the E–704 experiment, if perturbative QCD is applicable to these $p_T$ values at beam momentum $p = 200$ GeV/c. Moreover the experimental errors are large for $A_N$ at $p_T > 2.5$ GeV/c [11]. Therefore new experimental data with high statistics seem important for verification of some predictions of the QCD.

3. The SPASCHARM project
The SPASCHARM (SPin A symmetry in CHARMonia) is the project for world-class research works in fixed target mode for high energy spin physics [2, 3, 4]. The main goals of the SPASCHARM project are the studies of the (i) spin structure of the nucleon and (ii) possible spin dependence of the strong interaction for matter and antimatter with help of the systematic
physical analysis for a wide set of hadronic reactions and secondary particles. The same name experimental setup is the core part of the SPASCHARM project. It is suggested to have two stages of the SPASCHARM project: first of all, studies with unpolarized proton beams using a polarized target and second phase of the project is the using of polarized beams.

The polarized $p^+ (\bar{p}^+)$ beam is obtained by selecting $p^+ (\bar{p}^+)$ from the weak decay of $\Lambda (\bar{\Lambda})$ produced in a primary target by extracted proton beam. This method is used for both the E–704 experiment and the SPASCHARM setup. The main features are shown in table 1 for U–70 and Tevatron beams. As seen from table 1 there are some advantages of the expectations for U–70 (for instance, intensities for primary and polarized proton beams) with respect to corresponding Tevatron beam parameters. It should be noted the U–70 allows the study of single-spin asymmetry in deeply non-pertubative region for some range of $\sqrt{s}$.

| Beam parameter | U–70       | Tevatron   |
|----------------|------------|------------|
| 1 primary proton beam, $p$ (Gev/c) | 50–60      | 800        |
| 2 primary beam intensity, c$^{-1}$ | $\sim 2 \times 10^{12}$ | $1.5 \times 10^{11}$ |
| 3 polarized beam, $p$ (Gev/c) | 15–45      | 185 ± 17   |
| 4$^b$ beam intensity at the target, c$^{-1}$ | $(0.9 – 6.8) \times 10^6$ | $1.5 \times 10^6$ |
|   | $(0.8 – 4.0) \times 10^4$ | $1.5 \times 10^5$ |
| 5$^b$ beam polarization | ±(0.45 ± 0.05) | ±(0.40 ± 0.12) |
|   | –//–        | ±(0.45 ± 0.03) |

$^a$The minimum (maximum) relative uncertainty for beam momentum $\delta p$ is 4.5% (11%) for $p = 15$ GeV/c and 3.0% (9.0%) for $p = 45$ GeV/c.

$^b$The first / second line corresponds to the $p^+$ / $\bar{p}^+$ beam.

Dependence of polarized beam intensity on momentum is shown in figure 2 for $p$ (left) and $\bar{p}$ (right). The difference in intensities of $p^+$ and $\bar{p}^+$ beams increases dramatically with a growth of beam momentum. As seen for polarized proton beam the contribution of $\pi^+$ from neutral kaon decays is small, furthermore this contribution decreases rapidly with beam momentum. Therefore the U–70 allows the polarized proton beam with good quality (purity). Figure 2 (right) shows that the beam of $\bar{p}^+$ with $p = 16$ GeV/c seems optimal in terms of intensity and background conditions. The number of $\pi^-$ is approximately 3 times higher than the intensity of the antiproton beam. The separation of antiprotons at this level of background is quite possible with the help of Cherenkov beam counters.

The SPASCHARM detector is an open geometry setup with good particle identification and relatively large acceptance. Schematic view of the SPASCHARM is shown in figure 3. The SPASCHARM setup consists of the following main subsystems [2, 4]:

– various targets (liquid hydrogen, nuclear from Be up to Pb; polarized / unpolarized),
– spectrometer for registration of charged particles (magnet, GEM detector, multiwire proportional chambers – PC and drift ones – DC),
– electromagnetic calorimeter (ECAL) is shown in figure 4 and it is made by "shashlik" technology which is well established and used successfully, for instance, during preparation the PANDA experiment,
– hadronic calorimeter (HCAL),
– set of detectors for particle identification and multiplicity measurement (ring image Cherenkov detector – RICH, muon spectrometer – MuD and time-of-light system – TOF).
Figure 2. Intensity for beam of $p^+$ (left) and $\bar{p}^+$ (right) along with pion background of appropriate sign of electric charge for maximum $\delta p$ shown in table 1. The quantity is calculated for $10^{13}$ primary protons with energy 60 GeV, where $\xi_y$ is the transverse polarization averaged over ensemble. Data are taken from [4].

Figure 3. Schematic 3D view of the SPASCHARM setup. Here liquid hydrogen target (TGT) is shown, DT1–5 – a sets of thin-walled drift tubes, other subsystems are described in the text. Distances are shown in meters along the beam direction with respect to the center of the target.

Subsystems of the SPASCHARM detector are designed for high quality particle identification. According to the Conceptual design report (CDR) [4] the SPASCHARM will provide registration of charged particles from 0.5 up to 50 GeV/c in full azimuth $2\pi$, registration of $\gamma$ from 0.2 up to 50 GeV/c with the same angular range as for charged particles, identification of charged particles for momentum domain 1–20 GeV/c, registration of decay particles from hyperons with future reconstruction of parent particle, high coordinate resolution for beam particles, especially, for elastic scattering study [4]. Furthermore there are following special requests for charmonium
study: momentum resolution is \( \sim 2\% \) at 10 GeV/c and energy resolution for electromagnetic calorimeter is \( 3\%/\sqrt{E} \). Therefore there are some advantages of the SPASCHARM project regarding to earlier experiments, for instance, E–704. In particular, addition of new detectors (GEM, MDC, high quality EMC etc.) allows the increase of statistics significantly compared to the previous experiments. Due to \( 2\pi \) acceptance on azimuthal angle of the SPASCHARM setup one can expect that the systematic errors in \( A_N \) will be small. With the use of polarized proton beam at SPASCHARM a precision measurement of \( A_N \) for inclusive production in the transverse polarized beam fragmentation region in a wide \((x_F, p_T)\)-region will be worthwhile [2]. One can expect that the kinematic ranges \( 0.2 < x_F < 1.0 \) and \( 0.5 < p_T < 3.5 \) GeV/c will be covered. Also the estimations will be obtained for accuracy of the \( A_N \) measurement in the reactions (1), (2) and for corresponding time of data collection for various accelerator parameters (beam intensity, run duration etc.).

Within SPASCHARM project the software is constructed for on-line and off-line data analyses. The software is developed as object-oriented environment and it is based on the ROOT package. Also SPASCHARM software includes GEANT 3, 4 and some event generators (PYTHIA, PLUTO etc.) for Monte-Carlo simulation of hadronic interactions. At present the software environment SpascharmRoot has been developed and partially implemented. The SpascharmRoot allows the simulation, reconstruction, on- and off-line analysis of experimental data. The environment is under active development. The SPASCHARM software is permanently improving, for instance, the possibility is considered for using of the GRID technology for distributed data analysis.

4. Summary
Analyzing power shows the significant magnitude for inclusive pions above \( p_T \sim 0.5 \) GeV/c but there is only one measurement of the \( A_N \) for inclusive pions with polarized antiproton beam. At present phenomenological models describe the experimental data at qualitative level only and precision of experimental results do not allow the clear discrimination between various models. Consequently the new high-precision measurements seem important for better understanding of single-spin asymmetry and more definite physics conclusions. Hopefully, the SPASCHARM experiment will provide the high-statistics data which will shed new light for single-spin pion asymmetry as well as in general for spin structure of the proton.

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