Polarimeters for the SPASCHARM Experiment

P. A. Semenov^{*,†,§}, A. A. Bogdanov[†], S. I. Bukreeva^{*}, M. A. Chetvertkov[‡],
 V. A. Chetvertkova[‡], V. I. Garkusha^{*}, A. P. Meshchanin^{*}, V. V. Mochalov^{*,†},
 S. B. Nurushev^{*,†}, M. B. Nurusheva[‡], M. F. Runtso[†], A. V. Ridiger[‡], V. L. Rykov[†],
 S. V. Ryzhikov^{*}, M. N. Strikhanov[†], A. N. Vasiliev^{*,†} and V. N. Zapolsky^{*}

^{*}State Research Center Institute for High Energy Physics, Protvino, 142284, Russia

[†]National Research Nuclear University, Moscow Engineering Physics Institute,
 Moscow, 115409, Russia

[‡]Federal State Budget Organization State Center Interfizika, Moscow, 115409, Russia

[§]Corresponding author. E-mail: psemenov@ihep.ru

Published 29 February 2016

A beam channel of polarized protons and antiprotons produced from decays of Λ - and anti- Λ -hyperons for the SPASCHARM experiment is to be built at IHEP U-70 accelerator in Protvino, Russia. The methods for tagging and measuring polarization of the beam (anti)protons are discussed in this report. The fast on-line beam tagging exploits the correlations between polarization and kinematics of (anti)protons originated from (anti) Λ -decays. In the intermediate focus of primary target, decay (anti)protons of different transverse polarizations are spatially dispersed transversely with respect to the beam axis. The tagging system, consisting of fast beam detectors with good spatial resolution, measures the momentum and trajectory of each beam particle, including its position at the intermediate focus, thus allowing instant (on-line) assignment of the transverse polarization value to each (anti)proton. This system is also extremely useful for the beam channel tuning. While being fast and convenient, the polarization tagging fully relies on computing of particle transportation in the beam channel. In order to verify the real beam polarization and operating of the tagging system and beam channel, the independent absolute beam polarimetry is to be used. It is based on measuring the spin asymmetries in elastic scattering of beam (anti)protons in Coulomb-Nuclear Interference (CNI) and diffractive kinematic regions. It is estimated that less than one week of data taking would allow measuring an absolute beam polarization at the statistical accuracy of $\sim 4\text{--}5\%$.

Keywords: Spin; polarization; asymmetry; decays; protons; antiprotons; tagging; elastic scattering.

PACS numbers: 41.85.-p, 13.30.-a, 13.88.+e, 13.85.Dz

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 3.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

1. Introduction

The new experimental program SPASCHARM [1, 2] for 70 GeV proton synchrotron (U-70) is currently under development at the Institute for High Energy Physics (IHEP), Protvino, Russia. The main physics motivation for the SPASCHARM experiment is the systematic study of spin phenomena for a wide range of inclusive and exclusive reactions in collisions of high-energy polarized hadrons. The experiment will be carried in two stages. At the first stage, the study of single-spin asymmetries will be performed, using unpolarized meson and proton beams interacting with the transversely polarized protons of the “frozen” target [3]. At the second stage, polarized proton and antiproton beams will be available along with the polarized target at the new SPASCHARM beam channel 24A. The physics programs for the both stages of SPASCHARM experiments have been presented in Refs. [1, 2]. In this report, we address the issue of tagging the polarization of beam (anti)protons as well as independent measurements of absolute polarization of the selected beam samples in order to verify the tagging validity and performance.

2. Polarized Proton and Anti-Proton Beams

The polarized protons and antiprotons^a in the proposed beams for the 2nd stage of SPASCHARM experiment are produced by parity-violating decays of Λ -hyperons: $\Lambda \rightarrow p\pi^-$ or $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. This method had been suggested ~ 45 years ago by Overseth and Sandweiss [4, 5] and then successfully used in E581/E704 experiment [6] at Fermilab and FODS experiment [7] at IHEP.

The optical schema of the SPASCHARM polarized proton beam channel 24A is shown in Fig. 1. It is designed for polarized proton momenta of up to 50 GeV/c. The high-intensity 50–60 GeV/c primary proton beam of up to $2 \cdot 10^{13}$ protons per cycle is slowly extracted from U-70 and steered (from left to right in Fig. 1) onto the

Fig. 1. Optical schema of the SPASCHARM polarized proton channel 24A: Q are quads, M —dipoles, K —collimators, T is the primary target and T_{exp} is the experiment’s one. The intermediate focus (see text below) is located at the position of vertical collimator $K4$ in between $Q6$ & $Q7$.

^aIn the rest of paper, we usually mention for brevity only “protons” and “ Λ -hyperons” although, in most cases, the respective statements are applicable to “antiprotons” and “anti- Λ -hyperons” too, often with some quite obvious modifications.

Fig. 2. Λ -decay process and virtual source of polarized protons.

primary external target T where Λ -hyperons are produced and then decay, serving as a source of a tertiary polarized proton beam.

The principle of generating transversely polarized protons is illustrated in Fig. 2. In the parity-violating decays: $\Lambda \rightarrow p\pi^-$, protons are produced longitudinally polarized in Λ rest frames with helicity close to +64%. When boosted to the laboratory frame, protons obtain a transverse polarization component which depends on the proton emission angle. As a result, a proton transverse polarization correlates with the transverse position at the virtual source in the primary target plane. These correlations are smeared with the primary beam size, variations of distance of decay point from the primary target, and momentum spread of protons.

For the SPASCHARM beam, the computed dependences of vertical transverse proton polarization on the vertical position at the virtual source are presented in Table 1 for two momentum spreads $\Delta p/p$. The actual tagging of polarization takes place at the intermediate focus (see Fig. 1) where the virtual source is reproduced as an inverse image, magnified by a factor of 1.7.

The proposed tagging station is similar to the hodoscope system used in E581/E704 experiment [6]. Schematically, it is shown in Fig. 3. It consists of nine 16-channel overlapping scintillator hodoscopes. Three hodoscopes, $POL1-POL3$, of the size $X \times Y = 70 \times 132 \text{ mm}^2$ will be positioned close to the intermediate focus. They will measure the vertical displacement for each beam proton which, in turn, is related to the proton vertical polarization. The momentum analysis is performed in horizontal plane, using the hodoscopes $MOM1-MOM6$.

Table 1. Proton beam polarization at the virtual source for proton momentum $p = 45 \text{ GeV}/c$.

Vertical displacement, mm	Polarization, $\Delta p/p = \pm 1\%$	Polarization, $\Delta p/p = \pm 5\%$
± 40	$\pm 58\%$	$\pm 53\%$
± 30	$\pm 54\%$	$\pm 50\%$
± 20	$\pm 48\%$	$\pm 44\%$
± 15	$\pm 44\%$	$\pm 39\%$
± 10	$\pm 36\%$	$\pm 31\%$
± 5	$\pm 19\%$	$\pm 16\%$

Fig. 3. SPASCHARM beam tagging station.

The tagging allows selection of optimum beam part taking into account transverse vertical polarization, averaged over the sample, and the sample intensity. The SPASCHARM proton beam of required momentum within the range of 12–50 GeV/c, total intensity up to $\sim 10^7$ protons/cycle (U-70 cycle is ~ 9 sec) and the size $\sim 13 \times 11 \text{ mm}^2$ will be delivered to the 20 mm in diameter hydrogen target. The total intensity of the 14 GeV/c antiproton beam is expected to be up to $\sim 4 \cdot 10^5$ antiprotons/cycle.

3. Absolute Polarimetry

The beam-tagging system assigns an absolute polarization value for each beam particle relative to a known trajectory. However, for the sake of data reliability, an independent measurement of beam polarization is a must in order to confirm those values and the operation of the beam tagging system. A combined polarimeter, measuring “left-right” asymmetry in elastic scattering of transversely (vertically) polarized protons at liquid hydrogen or polarized “frozen” target and covering the *CNI* region and, for redundancy, the diffractive momentum-transfer range as well, is to be used. It is shown schematically in Fig. 4. It consists of a number of scintillator hodoscopes and *GEM* detectors with the azimuth coverage of $\sim (15\text{--}17)\%$ of full 2π rad.

Its momentum transfer squared acceptance is from $-t > 0.001$ (for 45 GeV/c beam this corresponds to the scattering angle $> 0.7 \text{ mrad}$) through $\sim 0.5 (\text{GeV}/c)^2$. In diffraction region, the both, scattered and recoil protons, will be detected. But the *CNI* magnetic spectrometer will see only the scattered protons. In the time estimates

Fig. 4. Schematic view of the absolute polarimeter.

below, it is assumed that, for the proton beam absolute polarization measurements, the 20 cm long liquid hydrogen target will be used, and we selected only the beam sample with the average polarization of 40%, using the beam-tagging information, and the intensity of this beam sample is conservatively taken at 10^6 protons per U-70 cycle.

3.1. Diffraction polarimetry

The HERA Collaboration at IHEP performed fairly precise measurements [8] of analyzing power $P \equiv A_N$ (Table 2) for 45 GeV/c protons in the diffractive region at momentum transfers squared of $0.04 < |t| < 0.7$ (GeV/c)². The differential cross section has been measured in the same experiment [9] as well. In the most interesting interval of $0.075 < -t < 0.225$ (GeV/c)² with the sizeable average

Table 2. $P \equiv A_N$ in diffraction pp -scattering [8].

$-t, (\Gamma_3 B/c)^2$	A_N
0.04–0.075	0.03 ± 0.01
0.075–0.125	0.026 ± 0.002
0.125–0.175	0.023 ± 0.002
0.175–0.225	0.022 ± 0.002
0.225–0.275	0.016 ± 0.002
0.275–0.325	0.021 ± 0.004
0.325–0.375	0.009 ± 0.005
0.375–0.425	0.009 ± 0.005
0.425–0.475	0.009 ± 0.008
0.475–0.525	0.007 ± 0.010

$A_N \simeq (2.37 \pm 0.12)\%$ measured with the quite low, $\sim 5\%$, relative error, it is well described by the expression [9]: $d\sigma/dt = Ae^{bt}$, where $A = (84.8 \pm 3.5) \text{ mb}/(\text{GeV}/c)^2$ and $b = (11.42 \pm 0.35) (\text{GeV}/n)^{-2}$.

Using these data, one can estimate that, at a reasonable assumptions on data taking efficiency, it would take about 80–100 hours for measuring the beam sample's transverse polarization at the statistical error of $\sim 4\%$ (which is 10% of the expected average sample's polarization of $\sim 40\%$). For the estimation above, the polarimeter's effective t -acceptance has been assumed at $0.075 < -t < 0.225 (\text{GeV}/c)^2$.

3.2. CNI-polarimetry

The diffractive elastic scattering can reliably be used only at the beam momenta close to the points where the analyzing power $P \equiv A_N$ was already measured, but there is no a solid theory to reliably extrapolate it out for the other beam momenta. However, there is another process in pp elastic scattering, the Coulomb-Nuclear interference, in the kinematic region of a smaller momentum transfer squared $-t$ of $\sim 0.002\text{--}0.05 (\text{GeV}/c)^2$ which is quite well understood theoretically [10, 11]. Moreover, the CNI analyzing power A_N rather weakly depends on the beam momentum. Recently, it has been precisely measured at RHIC in BNL [12–14] for various beam momenta, some of which are within and some above the momentum range of interest for SPASCHARM. The A_N maximum of $\sim (4\text{--}4.5)\%$ is reached at $-t \simeq 0.003 (\text{GeV}/c)^2$, and its average for the interval $0.002 < -t < 0.05 (\text{GeV}/c)^2$, weighted with the cross section, can conservatively be estimated at $\sim 3\%$. An elastic scattering cross section for the same t -interval is estimated at $\sim 2.75 \text{ mb}$ [15]. Using these numbers and the same all other assumptions as for diffractive polarimetry above, one can find that it would take about 50–70 hours for measuring the absolute polarization of 45 GeV/c proton beam sample at the same as above statistical accuracy of $\sim 4\%$.

4. Summary

For the second stage of SPASCHARM experiment at the U-70 IHEP accelerator, the polarized proton and antiproton beam-channel will be built. The beam tagging system will measure the momentum and trajectory of each beam particle providing the polarization value assignment. The total intensity of the 45 GeV/c proton beam is expected to be $\sim 10^7$ protons/cycle, and for the 14 GeV/c antiproton beam, the intensity would be $\sim 4 \cdot 10^5$ antiprotons/cycle. The elastic scattering diffractive polarimetry would allow measuring the absolute beam polarization at the statistical errors of $\sim 4\%$ for about 80–100 hours (then the relative errors in the beam polarization value would be $\sim 10\%$). For the sake of redundancy and reliability, the other elastic scattering polarimetry, covering the CNI kinematic region, will be running simultaneously with the diffractive one. For the same exposition time, it could measure the absolute polarization of the same beam sample at about the same statistical accuracy. The described here combined polarimeter would be capable to provide a

reasonably quick feedback for verification of the beam tagging and confirmation of its and beam channel's proper operating.

Acknowledgments

We thank the IHEP management for their support of the SPASCHARM program. This work was supported in part by the RFBR grants # 12-02-00737-a and # 15-02-01669-a.

References

1. V. Mochalov, *Phys. Part. Nucl.*, **44**, No 6, 930–936 (2013).
2. V. Mochalov, “*Systematic Study of Spin Effects at the SPASCHARM Experiment*”, Report to the 21st Int. Sym. on Spin Phys., Peking University, Beijing, China, 20–24 Oct. 2014, These proceedings.
3. N. S. Borisov *et al.*, *Proc. of High-Energy Spin Physics Conf.*, Protvino, Vol. 2, 236 (1986).
4. O. E. Overseth, *Proc. of National Accelerator Laboratory 1969 Summer Study, Report SS-118 2250*, Available in eConf C69-06-09, 005 (1969).
5. O. E. Overseth and J. Sandweiss, *Proc. of National Accelerator Laboratory 1969 Summer Study, Report SS-120 2250*, Available in eConf C69-06-09, 006 (1969).
6. D. P. Grosnick *et al.*, *Nucl. Instrum. Meth. A*, **290**, 269 (1990).
7. V. N. Zapolosky *et al.*, *Proc. of 1993 Particle accelerator Conference*, Washington DC, USA, 1993, Vol.1, pp. 454–456.
8. A. Gaidot *et al.*, *Phys. Lett. B* **61**, 103 (1976).
9. C. Bruneton *et al.*, *Nucl. Phys. B* **124**, 391 (1977).
10. B. Z. Kopeliovich and L. I. Lapidus, *Sov. J. Nucl. Phys.* **19**, No 1, 114 (1974).
11. N. H. Buttimore *et al.*, *Phys. Rev. D* **59**, 114010 (1999).
12. A. Bazilevski *et al.*, *Journal of Phys.: Conf. Series* **295**, 012096 (2011).
13. I. G. Alekseev *et al.*, *Phys. Rev. D* **79**, 094014 (2009).
14. L. Adamczyk *et al.*, *Physics Letters B* **719**, 62–69 (2013).
15. V. D. Apokin *et al.*, *Soviet Journal of Nuclear Physics*, v. 25, 51–55 (1977).