SPIN PHYSICS PROGRAM IN THE U70 POLARIZED PROTON BEAM

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Abstract

A possibility to accelerate a high intensity polarized proton beam up to 70 GeV at the IHEP accelerator, extract it from the main ring and deliver to several experimental setups is being studied now. We propose to study a wealth of single- and double-spin observables in various reactions using longitudinally and transverserly polarized proton beams at U70. The proposed measurements can be done at the existing detectors as well as require to create a few new experimental setups at U70.

Introduction

We propose to produce polarized proton beam from the polarized atomic beam source, accelerate it in the 1.5 GeV booster and then in the U-70 main ring up to 70 GeV, extract it from the main ring and deliver to several experimental setups to:

- measure the gluon and quark polarization in longitudinally polarized protons in charmonium production to help to solve the problem of "spin crisis";
- measure the double-spin transversity distribution in transversely polarized protons by using the Drell-Yan muon pair production;
- measure dependence of single-spin asymmetries(SSA) on separate kinematic variables p_T and x_F and hadron type to study the possible non-perturbative origion of SSA;
- measure miscellaneous spin parameters in hyperon production at moderate transverse momenta to learn about role of strange quarks in the spin structure of nucleon;
- measure polarization and spin correlation parameters in elastic pp-scatering in the hard scattering region in order to check the QCD predictions.

Although years of experimental effort at miscellaneous accelerators have provided a lot of information about the QCD hard scattering and the parton structure of the proton, there is no corresponding body of data on the spin-dependence of the elementary interactions and the spin structure of the proton. High intensity polarized proton beam accelerated up to 70 GeV and extracted from the U70 main ring offers the opportunity to study the unique properties of the spin variable at large x to increase the understanding of these fundamental quantities.

Final goals of spin physics at U70 are :

- study the spin structure of the proton, i.e., how the proton's spin state can be obtained from a superposition of Fock states with different numbers of constituents with nonzero spin;
- study how the dynamics of constituent interactions depends on spin degrees of freedom and on the flavors;
- understand chiral symmetry breaking and helicity non-conservation on the quark and hadron levels;
- study the overall nucleon spin structure in the range of moderate p_T(up to 5 GeV/c), and the long range QCD dynamics (confinement), including study non-perturbative interactions of massive constituent quarks with an effective color field of flux tubes, produced by confined quarks and gluons.

These issues are closely interrelated at the hadron level and the results of the experimental measurements are to be interpreted in terms of hadron spin structure convoluted with the constituent interaction dynamics.

1 Acceleration of Polarized Protons at U70

To do this spin physics, the polarized proton beam with an intensity up to 10^{12} protons per spill and energy up to 70 GeV needs to be accelerated. This process starts from an intensive polarized proton source. A polarization value of the beam needs to be measured continuosly by polarimeters. The setups should include polarized targets if double-spin measurements are being planned.

To achieve high luminosity in the interactions of polarized beams with the targets, the intensity of the planned polarized proton source should be sufficient. This source is expected to be designed and built at the Institute of Nuclear Research, Troitsk. It will be an atomic beam-type polarized ion source. The source might produce up to 5 mA of H^- with 90% polarization.

During acceleration, the polarization may be lost when the spin precession frequency passes through a so-called depolarizing resonance. These resonances occur when the spin tune $\gamma\times$G (where G=1.793 is the anomalous magnetic moment of the proton and γ=E/m) is equal to an integer number (imperfection resonances), or equal to kP$\pm\nu_z$ (intrinsic resonances). Here P=12 is the superperiod of the U70 accelerator, ν_z=9.9 is the vertical betatron tune, and k is an integer. Imperfection resonances are due to vertical closed orbit errors and intrinsic resonances are due to the vertical betatron motion. It is possible to preserve a high polarization value, sort of 70% over the acceleration of the polarized proton beam up to 70 GeV if one installs three partial siberian snakes in the main ring of the U-70 with the snake "strength" W=ϕ /2 π = 0.18. Three definite long streight line sections (4.87 m each) in the U-70 main ring need to be cleaned up from the existing equipment. Much more details can be found in the report of Yu.M.Shatunov [1].

There should be two types of polarimeters at U70 : 1) absolute polarimeter to determine a value and a sign of polarization with a high accuracy and 2) less accurate but fast relative polarimeter. The both polarimeters should be based on Coulomb-Nuclear Interference (CNI) effect. The absolute polarimeter could be built with the use of a polarized jet target, while the relative polarimeter with the use of Carbon thin target. The absolute polarimeter calibrates the relative one. The polarization of proton beam circulated in the U70 averaged over 100 hours data taking could be measured to 10% statistical accuracy with the use of hydrogen jet. The detail description of the polarimetry for U70 can be found in the report of S.B.Nurushev [1].

Longitudinally and transversely polarized targets are needed for double-spin measurements. The effect of a high intensity polarized proton beam is to deposit a significant amount of heat in the target. It is thus necessary to use ^{4}He evaporation refrigirators to cool the target, instead of dilution refrigirators, even though the lower temperatures achievable in dilution refrigirators often results in higher polarizations. A second effect of the high intensity beam is a significant amount of radiation damage in the target material. Materials that are chemically doped typically perform poorly under conditions of high-radiation damage, so radiation-doped materials, typically ammonia ($^{15}NH_3$) or lithium (^{6}LiD) hybrides, are used. These continuous pumping polarized targets are the best ones to work with high intensity beams up to 10^{11} p/[cm$^2\times$ sec].

2 Single-Spin Asymmetries in Inclusive Processes

The studies of the spin effects in inclusive processes probe the spin dependence of the incoherent hadronic interaction dynamics. The cross–sections of the hard production processes are described in the perturbative QCD as a convolution integral of parton cross-sections with the light–cone parton densities. The primary goal of the single-spin measurements with hadronic final states would be a study where the onset of perturbative QCD regime occurs. It is usually assumed, that single-spin transverse asymmetries in inclusive process $A+B\to C+X$, where A is a polarized hadron, have higher twist origin [2, 3]. The contribution of higher twists should be small at high energies and at small distances $l\sim 1/Q$. There are some indications that such contributions are small even at not too high energies and Q^2 values. In particular, it follows from the recent data on the spin structure function $g_2(x)$ obtained at SLAC. If it is the case, the observed significant one-spin asymmetries in hadronic processes are to be associated with the manifestation of a nonperturbative dynamics.

The measurements of one-spin transverse asymmetries will be important probe of the chiral structure of the effective QCD Lagrangian.

The available experimental data are at some variance with PQCD predictions: these data do not at least show up tendency to converge to the vanishing single-spin asymmetries in inclusive and elastic hadron productions. Several mechanisms have been proposed for the explanation of the observed single-spin effects.

Single transverse spin asymmetries in hard processes are expected to vanish in perturbative QCD at the leading twist (twist-2) level, however this is no longer true if one considers higher twist contributions. Twist-3 contribution [3] leads to a potentially larger asymmetry. A measurement of higher twist effects not only provides a valuable test on perturbative QCD, it also yields information on the hadron structure. The higher twist distributions represent correlations between quarks and gluons inside a hadron. These correlations have specific structures in QCD. If extracted from experimental data, they provide useful constraints on nucleon models, in particular, the non-valence degrees of freedom that include sea quarks and gluons.

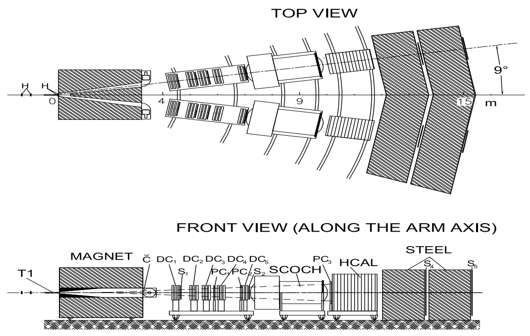

Figure 1: Experimental setup FODS.

Other world wide known possible sources of the observed one-spin asymmetries could be: correlation of $k_\perp$ and spin in initial state [4] (Sivers effect) and fragmentation [5] functions (Collins effect). Usually we have combinations of these effects together with Twist-3 effect in a particular experiment and special technics are required to extract them from observed asymmetries. There are also other theoretical approaches to explain large single-spin asymmetry in inclusive hadron reactions such as rotation of valence quarks inside a hadron [6] and the coherent rotation of the quark matter inside the constituent quarks [7]. The Stern-Gerlach type of force [8] which acts on chromomagnetic quark moment in color flux tube field [9], is able to explain many features of SSA dependence on hadron type and kinematic variables.

The study of charged hadron inclusive reactions at U-70 energies is important as a clear test of perturbative QCD regime and nonperturbative dynamical models. In general, these studies are important for the understanding of the QCD vaccuum and transitions between the perturbative and nonperturbative phases. A detailed high precision study of SSA dependence on kinematic variables and hadron type allows to discriminate some of the proposed models and the origion mechanisms.

Asymmetries in inclusive production of charged pions, kaons, protons and antiprotons can be measured by FOcusing Double Arm Spectrometer (FODS) which is placed at the beam line 22 at IHEP. The experimental setup FODS is shown in Fig. 1. It consists of the analyzing magnet, drift chambers, spectrometer of Cherenkov radiation (SCOCH) for particle identification (charged pions, kaons, protons and anti-protons), scintillation counters and hadron calorimeters to make trigger on high energy hadrons. There are two arms which can be rotated around the target center situated in front of the magnet to change secondary particle angle. The radiation shielding in the beam line allows to work with a beam intensity up to 10^{10} p/sec, and the setup up to 10^9 p/sec.

The following single-spin measurements can be done at FODS:

- Precise measurements of A_N in inclusive production of charged pions, kaons, protons and antiprotons at hydrogen and nuclear targets. Large x_T can be achieved. To separate p_T and x_F asymmetry dependences, the measurements at several angles are needed (might be done in the range of 10-130^0 in c.m.).
- Measurements of A_N in symmetric hadron production. Symmetric pairs (π^+ and π^-,etc) are the hadrons produced in the c.m. with about the same momenta and moving in the opposite directions. For these processes k_T is almost zero and there is no Sivers effect.
- Measurements of A_N in Drell-Yan muon pairs. There is no fragmentation in this process - this means that there is no Collins effect. (Additional absorbers in each arm will be installed).

3 Measurements of Quark Transversity Distributions in a Polarized Proton

From deep inelastic scattering, one can measure $f_1(x)$ related to the spin-averaged longitudinal momentum distribution of quarks in the nucleon and $g_1(x)$ related to the helicity distribution in a longitudinally- polarized nucleon. In addition to these two well-known structure functions, there exists a third fundamental function, $h_1(x)$, which is a leading twist (twist-2) distribution function like $f_1(x)$ and $g_1(x)$. This third function, which has never been experimentally determined, is accessible by measuring the double transverse spin asymmetry A_{TT} in certain processes with both beam and target protons transversely polarized.

A measurement of $h_1(x)$ can shed interesting light on the spin structure of the nucleon. In fact, in non-relativistic quark models, the transversity distribution is identical to the quark helicity distribution $g_1(x)$. Thus, a comparison between the sizes of $h_1(x)$ and $g_1(x)$ would measure the success of these models in treating the spin degrees of freedom. The function $h_1(x)$, unlike the helicity function $g_1(x)$, cannot be measured in deep inelastic scattering due to its different properties under chiral transformations.

Quark transversity is a new observable for understanding the hadron wave function in terms of bare quarks. Gluons give no contribution to the transverse spin of the proton. It is promising to explore this new spin observable and compare it with the longitudinal spin densities. With transversely polarized beams the new field of transverse spin effects can be explored in the Drell-Yan muon-pair channel by measuring the correlation of the plane of the muon-pair to the spin axis. This provides a clean approach to quark transversity, h_1(x).

A beam dump experiment might be an appropriate one to measure transversity in Drell-Yan muon pairs. The scheme of the experiment is as follows. A polarized beam interacts with a polarized target. There is an absorber just after the target and finally a muon detector to detect Drell-Yan muon pairs. An issue will be a hadronic background which can originate from decays of charged pions and kaons before reaching the absorber and from hadrons penetrating the material (punch-through).

If the polarized target can accept an intensity of 10^{11} p/spill (we expect spill duration of 3 s out of 9 s full cycle), then the luminosity of this experiment would be about 10^{34} cm^{-2} s^{-1} that is three orders of magnitude higher than today at RHIC or at the planned PAX at GSI. The region of x_1x_2=0.02-0.09 for the Drell-Yan masses between 1.5 and 3 GeV/c^2 will be covered. These measurements will be complementary to the RHIC and PAX ones, where the covered regions are expected to be 0.004-0.02 and 0.07-0.3, correspondingly. The estimated numbers of Drell-Yan events for 30 days at beam are about 180,000 and 24,000 for the masses of 1.5 and 2.0 GeV/c^2, respectively. The A_{TT} errors for these masses are expected to be in the range of (2-4)%.

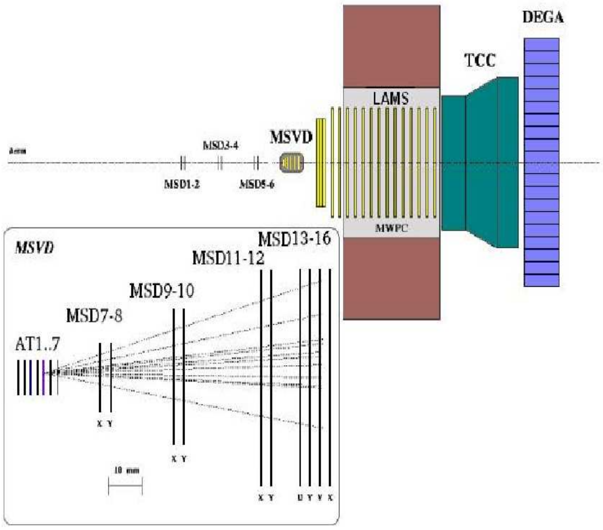

Figure 2: Experimental setup SVD-2.

4 Measurements of Spin Effects in Strange Hadron Production

It is evident from deep–inelastic scattering data that strange quarks as well as gluons could play essential role in the spin structure of nucleon. DIS data show that strange quarks are negatively polarized in polarized nucleon, $\Delta s \simeq -0.1$. Elastic νp-scattering data provide the value $\Delta s = -0.15 \pm 0.08$ [10]. The presence and polarization of strange quarks inside a hadron should give an experimental signal in hadronic reactions also.

Experimental situation with hyperon polarization is widely known and stable for a long time. Polarization(P_n) of Λ–hyperon produced in the unpolarized inclusive pp–interactions is negative and energy independent. It increases linearly with x_F at large transverse momenta ($p_\perp \geq 1$ GeV/c), and for such values of transverse momenta is almost $p_\perp$-independent.

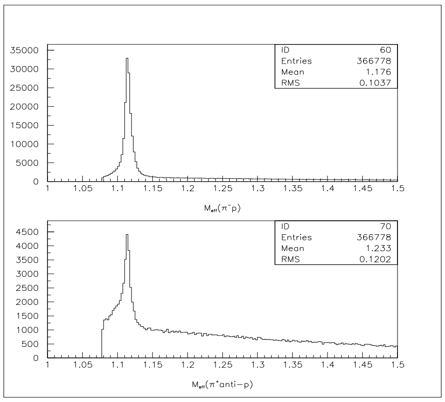

Figure 3: Spectra of π^-p invariant masses (upper part) and π^+anti-p (lower part).

We consider the production of hyperons in the kinematic region of p_T from 1 to 5 GeV/c and at large x_F. A systematic study of many spin observables (P_n, A_n, D_{nn}, A_{LL}, etc.) with polarized beam and polarized target for the different hyperon productions could be done with the use of the U-70 polarized beam. The measurements can be done at the existing experimental setup SVD-2 (see Fig. 2) which is placed at the beam line 22 at IHEP and consists of a) the high-presicion microstrip vertex detector(MSVD) with active(Si) and passive(C,Pb) nuclear targets(AT), b) the large aperture magnetic spectrometer(LAMS) with two sets of MWPC(multiwire proportional chambers), c) the multicell threshold Cherenkov counter(TCC), and d) the gamma quanta detector (DEGA). The mass spectra of Λ-hyperons are shown in Fig. 3 to demonstrate the setup capability to detect hyperons. More than 200,000 Λ-hyperons were recently detected over one month of data taking with a beam intensity of 0.5×10^6 protons/sec. Λ-hyperons are very well detected in the beam fragmentation region where large spin effects are expected.

Spin effects in strange hadron production shed light on the role of strange quarks in the spin structure of nucleon and non-perturbative QCD dynamics.

5 Double Spin Asymmetry in Charmonium Production

The study of spin effects in some processes would yield information on the contribution of the spin of quarks $\Delta\Sigma$ and gluons ΔG and orbital angular momenta of quarks L_q and gluons L_g into the hadron helicity:

$$1/2 = 1/2\Delta\Sigma + L_q + \Delta G + L_g \qquad (1)$$

In the above sum all terms have clear physical interpretation, however besides the first one, they are gauge and frame dependent. Transparent discussion of the theoretical aspects of this sum rule and a new gauge independent one are given in [11]. Gluon contribution into the proton spin was worldwide studied at HERMES, COMPASS, RHIC, JLaB and SLAC, however new data especially at large x are very appreciated.

We propose to simultaneously measure the double-spin asymmetry A_{LL} for inclusive χ_2, χ_1 and J/ψ by utilizing the 70 GeV/c longitudinally polarized-proton beam on a longitudinally polarized target. Our goal is to obtain besides the quark-spin information also the gluon-spin information from these three processes in order to determine what portion of the proton spin is carried by gluons. We anticipate obtaining significant numbers of χ_2, χ_1 and J/ψ events. The statistical errors on A_{LL} will be small enough for the possible determination of the spin-dependent gluon structure function in a specific x range where the gluon polarization is expected to be sizeable. This would be the world's first measurement of gluon-spin information and of spin effects in charmed-particle production in hadron-hadron inter-

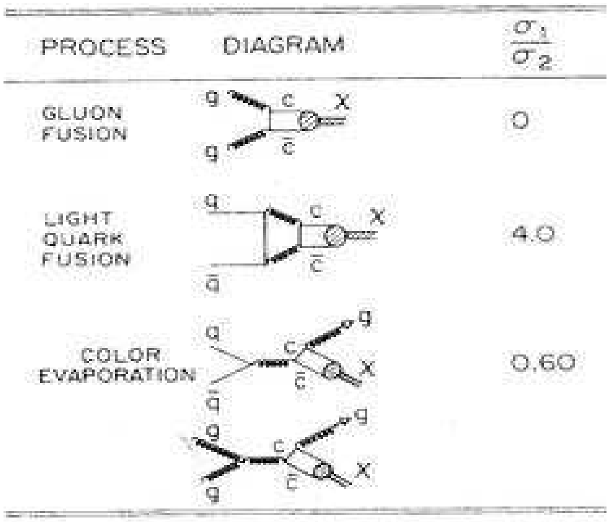

Figure 4: Lowest-order parton fusion diagrams for hadronic χ production.

actions. The same proposal at Fermilab [14] at 200 GeV/c was not approved in 1991. The Fermilab PAC committee did not beleive that proper number of charmonium events would be collected by using low intensity polarized proton beam obtained from Λ-hyperon decays.

The hadronic production of the χ states involves three parton fusion diagrams (see Fig. 4): gluon fusion, light quark annihilation, and color evaporation [15]. However, the relative contributions of each subprocess and even the total cross section for charmonium production have proven difficult to calculate reliably. There are fairly definite predictions for the relative production rates of the χ states which may help distinguish among the models. The theoretical predictions for the ratios $\sigma_1/\sigma_2=\sigma(\chi(3510))/\sigma(\chi(3555))$ are as follows [16] : zero for gluon fusion, 4.0 for light quark fusion and 0.6 for color evaporation. One of possible way to measure such parton's polarization is a study of χ_c-meson production with the following decay into J/ψ and a photon and then $J/\psi \to \ell^+\ell^-$. It was shown in [17], that the angular distribution of the final photon and lepton pairs provides a direct way to measure the polarization of the initial quarks and gluons.

In this experiment the separation of χ_1(3510 MeV) and χ_2(3555 MeV) is possible. The matrix element for χ_1 production via gluon fusion is calculated to be zero according to the lowest-order QCD [15]. If few χ_1 events are detected, then gluon fusion is dominant in χ_2 production. If the number of χ_1 events is significant, we need to also include other processes in the calculations to determine ΔG/G. Note that $A_{LL}(p\uparrow N\uparrow \to \chi_1 + X)$ and the $\chi_1 \to J/\Psi + \gamma$ decay angular distribution will be measured simultaneously in this case, providing an additional input for understanding the production process and the value of ΔG/G near x=0.3. We propose to measure the A_{LL} asymmetry in the J/Ψ production via the $J/\Psi \to e^+e^-$ channel.

If all three charmonium production processes contribute, the measurement of χ_2, χ_1, and J/Ψ become equally important. The A_{LL} (χ_2, χ_1, J/Ψ) provide a test to various models, which predict opposite A_{LL} signs. The signs and magnitudes of $A_{LL}(\chi_2)$ and $A_{LL}(J/\Psi)$ will provide crucial information on the production mechanism(s), if the χ_1 production at 70 GeV in pp-interactions is not negligible compare to the χ_2 production. A large value of A_{LL} will indicate a sizeable ΔG/G independent of models.

The experimental setup in the open geometry configuration (see Fig. 5) will consist of electromagnetic calorimeter, proportional chambers and plastic scintillator-pad detector for the charmonium trigger.

In order to separate χ_1(3510 MeV) and χ_2(3555 MeV) peaks, the energy resolution of the calorimeter is important, especially for the produced γ's. According to the decay kinematics of χ_2, the γ's are effectively detected at very forward angle (up to 100 mrad). A calorimeter for detection of these γ's must have good energy resolution with fast response to handle the rates.

The central part (Θ_{lab} from 10 mrad to 100 mrad) of the calorimeter system consists of 1140 blocks of lead tungstate (2.8 $\times$ 2.8 $\times$ 22 cm^3 per each block) to ensure good energy resoltion of the γ detection. This is an array of 34x34 blocks with a hole of 4x4 blocks in the center for non-interacted beam. The properties of lead tungstate (PWO) calorimeters have been extensively studied at IHEP over last several years [18]. The energy resolution of 2% at E = 1 GeV has been measured. The 1875 lead-glass counters (3.81 $\times$ 3.81 $\times$ 45 cm^3 per each block) cover a large area (Θ_{lab} from 100 mrad to 200 mrad). This is an array of 50x50 blocks with a hole of 25x25 in the center to accept the lead tungstate blocks.

The GAMS-2000 experiment [19] at IHEP used the same kind of lead-glass blocks with a similar setup in this proposal. The χ states have been detected by measuring e^+,e^-, and γ. Clear J/Ψ and χ peaks were observed with an open geometry configuration at a beam energy of 40 GeV, but no separation between the two χ-states was performed due to poor energy resolution.

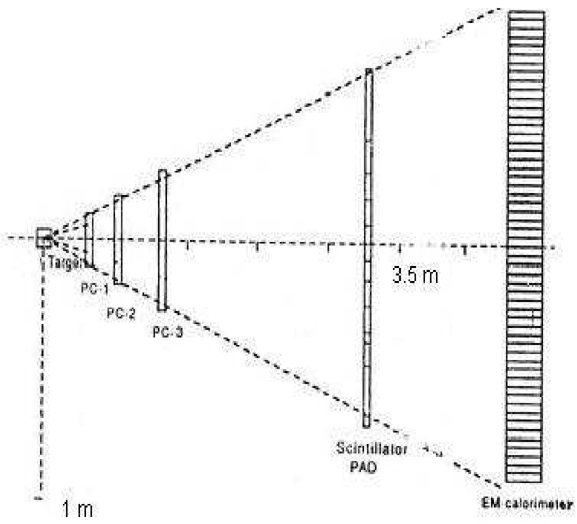

Figure 5: Schematic view of experimental setup to measure A_{LL} in χ and J/Ψ production.

The proportional chambers placed between the target and the calorimeter serve to track e^+ and e^- particles and assure that there are no charged tracks in the γ direction. The scintillator-pad trigger hodoscope containing 100 pads has a segmented mosaic structure. Our first estimate shows us that we might anticipate about 10,000 reconstructed χ_2 events/month and more than 50,000 J/Ψ events/month. A new experimental setup will have to be built to accomplish these measurements.

6 Polarization in Elastic Scattering

In perturbative QCD, there are several mechanisms that could give important contributions to fixed-angle elastic scattering. However, due to small cross–section studies of this exclusive process could be carried out in the region where nonperturbative effects are essential. There are several models based on nonperturbative dynamics predicting significant nonzero analyzing power at fixed angles(for example, [12, 13]).

The measurements of polarization in elastic pp-scattering (parameter A_N) can be done at the experimental setup “SPIN at U70” which is placed at the beam line 8 at IHEP. Both particles, forward and recoil protons will be detected by scintillation hodoscopes (forward arm) and by drift chambers (recoil arm). A resolution of the drift chambers will be about 200 μm. The setup can afford an intensity of the polarized proton beam up to 10^{12} p/spill. Particle identification will be performed by Cherenkov counters in the both arms and additionally by a time-of-flight technique in the recoil arm.

The parameter A_N in elastic pp-scattering will be measured at 70 GeV in a wide ${p_T}^2$ region - from 1 to 12 $(\mathrm{GeV/c})^2$. For 200 hours of data taking statistical errors in A_N will be less than 1% for ${p_T}^2$ up to 6 $(\mathrm{GeV/c})^2$. For 600 hours errors in A_N will be about 3% for 10 $(\mathrm{GeV/c})^2$ and about 6% for 12 $(\mathrm{GeV/c})^2$. The results will be used to discriminate among several models describing the polarization in elastic scattering in the hard interaction region.

Conclusion

To accelerate the polarized proton beam in the existing U70 accelerator up to 70 GeV with intensity up to 10^{12} protons/spill and polarization up to 70%, the following main tasks need to be completed:

- a polarized H^- proton source up to 5 mA to be designed and built;
- the existing equipment to be removed from three definite straight sections (4.87 m each);
- three partial siberian snakes to be installed in the U70 main ring in these three cleaned straight sections;
- the correction of the U70 vertical orbit to be done with +/-5 mm accuracy;
- an absolute(polarized jet target) and a relative polarimetry to be instrumented and installed into the U70 environment.

Acceleration of the polarized proton beam at U70 gives a brand new opportunity for the high energy spin physics in the new kinematic region - at moderate p_T (up to 5 GeV/c) and large x (parton momentum). The presented spin program includes five miscellaneous sets of measurements :

- polarization and double spin transverse asymmetry in elastic pp-scattering at large p_T;
- single spin asymmetry in inclusive charged hadron production ;
- miscellaneous spin parameters in hyperon production;
- transversity in Drell-Yan muon pairs;
- longitudinal double-spin asymmetry in charmonium production.

The results will be complementary to those which might be obtained at COMPASS, HERMES, RHIC, JLaB, GSI and JPARC.

The experiments at U70 at moderate p_T and large x will be the experiments of a new generation which will allow us to significantly excel the previous results in spin physics (in terms of statistics, wide kinematic region, types of hadron reactions). We hope that the results of spin studies at U70 will allow us to reject a part of proposed theoretical models and emphasize the most probable mechanisms of origion of spin effects.

Finally, we should mention that spin measurements at U-70 with polarized proton beam would probe the fundamental couplings of the underlying Lagrangian and investigate the spin structure of the nucleon. A variety of one- and two-spin asymmetries could be measured. As it has often happened in the past, these spin measurements might bring unexpected new results; this would certainly stimulate the development of new theoretical ideas.

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