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POLARIZATION STUDY

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Abstract

Nurushev S.B. Polarization Study: IHEP Preprint 89-169. - Serpukhov, 1989. - p. 33, figs. 10, tables 4, refs.: 35.

Brief review is presented of the high energy polarization study including experimental data and the theoretical descriptions. The mostimportant proposals at the biggest accelerators and the crucial technical developments are also listed which may become a main-line of spin physics.

Аннотация

Нурушев С.Б. Поляризационные исследования (Обзор): Препринт ИФВЭ 89-169. - Серпухов, 1989. - 33 с., 10 рис., 4 табл., библиогр.:35.

Дается краткий обзор поляризационных исследований в физике высоких энергий с описанием экспериментальных результатов и их теоретической интерпретации. Перечисляются наиболее важные проблемы, решения которых планируются вскоре на крупнейших ускорителях, а также методические разработки, достижения которых могут составить крупный этап в спиновой физике.

1. EXPERIMENTAL RESULTS

Introduction

During the year since the 9-th International Spin Symposium in Minneapolis /2/ and Fermilab Symposium /2/ a set of low and intermediate energy results have appeared (Saclay, TRIUMF, LAMF, JINR, ITEP) while the results in high energy region remained scarce (BNL, IHEP, CERN, FNAL). In the low energy region despite large accumulated data the problem of dibaryons has not yet been solved. The systematic study of the nucleon-nucleon elastic scattering is underway at Saclay, aimed at the reconstruction of amplitudes or phase shifts rather than at a deep insight into dibaryon resonances. At Saclay new technique of producing polarized neutron beams (quasimonochromatic) was developed as well as the rotation of their polarization by a solenoid. The new measurements were done also of $\Delta\sigma_T(np)$ and $\Delta\sigma_L(np)$ and other polarization parameters. Precise measurements were carried out of pion-nucleon elastic scattering at ITEP at energies 3 GeV/c, and at some angles the data severly contradict the existing phase shift analysis. The experiments using polarized deuterons are underway in JINR. The interesting results have been reported by KFTI and YEPI physicists on the photo- and electroproduction of pions.

At IHEP the study of inclusive reactions

$$\pi^- + p \to \pi^0(\eta) + X, \qquad (1)$$

at 40 GeV/c, large p_T ($\sim$ 3 GeV/c) and small x_F (in the vicinity of $x_F \simeq 0$, that is in the central region) is coming to its completion. These results and discussions will be presented later in this talk. The measurements at 70 GeV/c of the asymmetry in reaction

$$P + P \to \pi^0(\eta) + X, \qquad (2)$$

are planned to start at the end of C.Y. For the first time the 70 GeV circulating proton beam was extracted for such a study by a bent monocrystal.

At the beginning of the next year the first run will start in the E-704 at Fermilab. One foresees to measure $\Delta\sigma_L(pp)$ and $\Delta\sigma_L(\bar{p}p)$ and also asymmetry and spin transfer in the following reactions

$$p + p \to \pi^0 + X, \quad x_F \approx 0, \quad p_T \leqslant 3 \text{ GeV/c}, \qquad (3)$$

$$p + p \to \pi^\pm + X, \quad x_F < 1, \quad p_T \leqslant 1.5 \text{ GeV/c}, \qquad (4)$$

$$p + p \to \Lambda(\Sigma) + X, \quad x_F \leqslant 1, \quad p_T \leqslant 1.5 \text{ GeV}. \qquad (5)$$

For reaction (5) the final hyperon polarization will be also measured.

Physicists from Michigan University continue the A_N and A_{NN} measurements at BNL with the goal to reach the highest possible energy in elastic pp scattering (up to 22 GeV/c, see Fig.1). Recently, in BNL the spin transfer parameters D_{NN} were measured in Λ, Σ production. They are very close to zero in the whole momentum transfer region.

1. Elastic and Binary Reactions

Though no new experimental data are available at high energy, theoreticians attempt to put forward a hypothesis to interpret the already known results. For instance, particular attention was drawn to A_{NN}, measured at 18.5 GeV/c and p_T^2=4.7 (GeV)^2. The large value of A_{NN} at 12 GeV/c and its drastical decrease to zero at 18.5 GeV/c (see Fig.1b) can be explained in different ways:

- there are threshold phenomena, that is, the producion of Δ and N-resonances (Brodsky et al.[3]);

- A_{NN} oscillates with energy (Hendry[4], Troshin-Tyurin[5]).

In order to discriminate between these possibilities one should extend the energy region of measurements.

The next question is: what the A_N energy dependence is at fixed p_T. More than 16 years ago IHEP group presented such a dependence for $t=-0.2$ $(GeV/c)^2$ (see Fig.2). The data obtained later at the energies > 45 GeV are presented also without including the fit. The conclusions may be outlined as follows:

- polarization energy dependence is sensitive to the flavor of initial quarks;

- at small t the polarization decreases for all reactions with energy but in different ways;

- at large $t=-p_T^2$ polarization appears to be constant (see Fig.1a).

As is known from the available experimental data there is no equality between polarization of particles and antiparticles ($P_p \neq -P_a$), the S-invariance does not hold. The hypothesis on the possible arising of spin-flip from pomeron exchange came up from the equality of polarizations in proton-proton and antiproton-proton elastic scattering. This hypothesis was rather bold for that time, but now a lot of data have been acquired in this support.

In the Dubna model (Goloskokov et al[6]) there is an anomalous term corresponding to the spin-spin interaction and increasing with energy. This model gives a satisfactory description of differential and total cross-sections and predicts significant spin effects in the TeV region.

IHEP-JINR-TSU collaboration have measured the asymmetry at 40 GeV/c in the following charge-exchange binary reactions[10]

$\pi^- + p \to \pi^0 + n,$	(6)	$\pi^- + p \to f + n,$	(10)
$\pi + p \to \eta + n,$	(7)	$\pi + p \to K + \Lambda,$	(11)
$\pi^- + p \to \eta' + n,$	(8)	$\pi^- + p \to \pi^- + \pi^0 + n.$	(12)
$\pi^- + p \to \omega + n,$	(9)		

Most of the results are shown in Fig.3. In reaction (6) there are structures at $t=-0.2$, -0.5 and -1.2 $(GeV/c)^2$. We were not able to disentangle the following peculiarities due to large statistic errors. There are many model calculations aimed at explaining these data. Some of them are shown in Fig.3a.

There are several Redge model predictions for reaction (7) which agree with experimental data (Fig.3b). A relation was established for the polarization parameters in reactions (6), (7) and (8) (Enkovsky, Struminsky[7]):

$$P(\pi^0) + 2P(\eta) = P(\eta'). \tag{13}$$

This relation can be used for the determination of $P(\eta')$ and its comparison with experimental data. Such a comparison is shown in Fig.3c and the agreement is good enough.

Achasov et al.[8] calculated the asymmetry for reaction (9) (see Fig.3d). Some discrepancy is seen between the predictions and data but it may be explained by the difference between A and ρ_{11} for which the calculation was made.

The calculations for reaction (11) (Arestov et al.[9]) are shown in Fig.3e together with the experimental data, and there is an agreement within large experimental errors. Reactions (10) and (12) await their interpretation.

2. Inclusive Reactions at Large X_F

Under this item one can list the following results:

- IHEP-JINR-TSU collaboration measured asymmetries at 40 GeV/c in the following inclusive reactions[11]:

$$\pi^- + p \to \pi^0 + X, \tag{14}$$

$$K + p \to \pi + X, \tag{15}$$

$$\bar{p} + p \to \pi^0 + X, \tag{16}$$

$$\pi^- + d \to \pi^0 + X, \tag{17}$$

$$K + d \to \pi + X, \tag{18}$$

$$\bar{p} + d \to \pi^0 + X. \tag{19}$$

The results are presented in Fig.4. One can see that within the error bars asymmetries are consistent with zero. In the x_F dependence the asymmetry tends to change its sign in approaching high x_F values. Such a behaviour is consistent with the prediction of the triple Regge model.

In all abovelisted reactions the asymmetry does not depend upon the initial quark flavor. It would be very interesting to measure asymmetries versus the flavor of the final states.

Recently, the preliminary data on asymmetry were published for the reaction

$$p + p \to \pi^{0} + X, \qquad (20)$$

at the initial momentum of 185 GeV/c (E581/E704 collaboration at Fermilab[12]). The averaged asymmetry is equal to A_N=10±3)% and proves the persistence of spin effects at high energies (see Fig.5).

3. Inclusive Reactions at Large P_T

At IHEP the asymmetries were measured in the following reactions:

$$\pi^- + p \to \pi^0 + X, \qquad (21) \qquad\qquad \pi^- + p \to \eta + X, \qquad (23)$$

$$\pi^- + d \to \pi^0 + X, \qquad (22) \qquad\qquad \pi + d \to \eta + X \qquad (24)$$

at the initial momentum of 40 GeV/c and the kinematical region $-0.3<x_F<0.2$, P_T=1.2-3.2 (GeV/c)[13] (see Fig.6). One can see that asymmetries are the same for polarized proton and deuteron targets and also for π^0- and η-meson productions. The x_F dependences are very interesting: asymmetry increases when x_F varies from a positive to negative value, that is, in the direction of the polarized quark motion.

At present, three theoretical papers pretend to quantitavely describe these data. The first one (M.Ryskin, LINP[11]) establishes the relation between polarization and differential cross section

$$P \simeq \Delta q^2 \, \frac{d\ln\sigma(q^2)}{dq^2} \qquad (25)$$

(analogous to Fermi relation). The dashed line shows the results of this calculation (Fig.6). The second model (D.Sivers, ANL[15]) takes into account the transverse momentum distribution of constituent quarks inside hadron. In the high twist approximation this event can lead to one spin asymmetry at high momentum transverse. The prediction of this model is shown in Fig.6 by a solid line in comparison with experimental data. They coincide by the order of magnitude and prove the success of QCD in calculating the one spin asymmetry.

The dash-dotted line in Fig.6 presents the asymmetry in the central region, calculated by Troshin and Tyurin[16]. The experimental asymmetry is regarded by the authors as a manifestation of the gluon spin component.

4. Structure Functions

The scientific community is much interested in the measurements of hadron structure functions, which define in the parton model the x distributions of quarks and gluons inside hadrons. The EMC effect is known which shows the difference of parton distributions inside bound and unbound nucleons. Recently, the EMC collaboration measured the structure function $g_1^p(x)$ in deep-inelastic scattering of polarized muons on polarized protons. The amazing result of this experiment was as follows: the proton spin is not carried by valence quarks but mostly by gluons and orbital momentum. More than a dozen of theoretical papers were published attempting to explain the experimental data, and their conclusions were often contradictive. It is obvious that without a thorough experimental study it is impossibe to get an answer to the question: what the main source of nucleon spin is. One should emphasize in searching for the answer that only reactions with both initial particles polarized may shed light onto the spin structure problem, but not the one spin experiments. After this remark one can regard the experiments permitting to reconstruct ΔG (the gluon spin structure function):

1. Production and decay of J/ψ in Deep Inelastic Scattering (DIS) of polarized leptons on polarized nucleons;
2. Production and decay of $\chi_2(3555)$ in the two-spin hadron interactions;
3. Measurements of charmed particle distributions in DIS through decay $c(\bar{c}) \to \mu^+(\mu^-) + X$;
4. Asymmetry in hadron jet production in the collisions of polarized protons;
5. Direct photon production at large p_T;
6. Hyperon production with large p_T in pp-collisions;
7. High order effects in ep-interactions;

8. Drell-Yan lepton production in the interactions of polarized particles;

9. Hadron photoproduction at large p_T.

It stems from this list that one should have a set of polarized beams (h, l, γ) and a set of polarized targets. Not a single experiment from this list has been realized up to now.

5. Magnetic Moments

The possibility to produce polarized hyperon beam allows one to measure the hyperon magnetic moments with high precision. During last 10 years the data shown in table 1 have been accumulated (borrowed from J.Lach's paper/17/). In the same table the comparison is made with the additive quark model predictions. The largest deviations come up from the magnetic moments of the following particles: Ξ^0, Σ^+, Σ^- and Ξ^-. For comparison with theory the experimental accuracy is not quite satisfactory relevant for Ω^- magnetic moment and for transfer magnetic moment $\Sigma^0 \rightarrow \Lambda^0$. Experimentators are looking for new techniques in order to measure the magnetic moments of heavy quarks (c and b). Particularly, the use of bent monocrystals is seriously regarded as a method for measuring the magnetic moments of unstable particles.

Table 1. Magnetic moments of baryons

Baryons	Magnetic moments (μ_N)	Quark model (μ_T)	Difference $\Delta\mu=\mu_N-\mu_T$	Difference in σ	Difference in %
p	$(2792844.4\pm1.1)\cdot10^{-2}$	input			
n	$(1913043.08\pm0.54)\cdot10^{-6}$	input			
Λ^0		input			
Σ^+		2.67	$-(251\pm22)\cdot10^{-3}$	11.41	-9.40
Σ^-		-1.09	$-(66\pm14)\cdot10^{-3}$	4.71	6.06
$\Sigma^0\rightarrow\Lambda^0$		-1.63	0.02 ± 0.08	0.25	-1.23
Ξ^0		-1.43	0.177 ± 0.014	12.64	-12.38
Ξ^-		-0.49	-0.161 ± 0.017	9.47	32.86
Ω^-		-1.84	-0.16 ± 0.20	0.80	8.70

In general, the Table proves the success of the simple additive quark model. The masses of the u, d and s quarks calculated from their magnetic moments are equal to (in MeV/c^2) m_u=337, m_d=321 and m_s=509. These numbers agree with those derived from particle spectroscopy.

II. INSTRUMENTATION

Introduction

A success of spin physics is impossible without progress in the technique of production of polarized beams, polarimeters and polarized targets. Numerous teams work in all these directions and their achievements are obvious, for example, the acceleration of polarized protons at Brookhaven up to 22 GeV, production of polarized proton and antiproton beams at 200 GeV at FNAL (E-581); invention of the polarized target materials enriched with hydrogen, with high radiative resistance (NH_3, ^7LiH etc.); the first achievements in development of ultracold polarized jet target (Michigan/Brookhaven/MIT); assembling and testing of polarimeters on the basis of the Coulomb-nuclear interference and Primakoff effect (E-581); first tests of the prototypes of the spin snakes magnets.

The main goals of these technical developments are obvious: 1) one should have 100% polarized beams of the same intensity as it is for standard beam; 2) a pure polarized proton (and other) target with the polarization also close to 100%, the radiative resistant materials, polarization fast reverse; 3) absolute (relative) high efficient polarimeters.

Below a brief description is presented of the status of polarized beams, polarimeters, polarized targets, and also polarized jet targets.

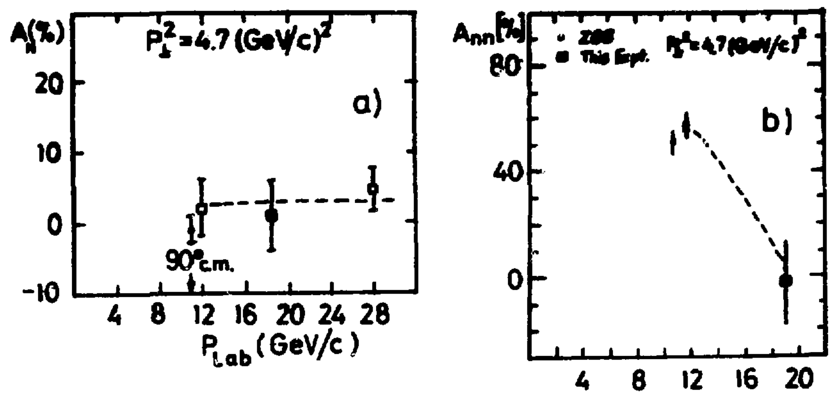


Fig. 1. Energy dependence in elastic pp-scattering at fixed p_T^2 = = 4.7 $(GeV/c)^2$ of parameters: a) A_n and b) A_{nn}.

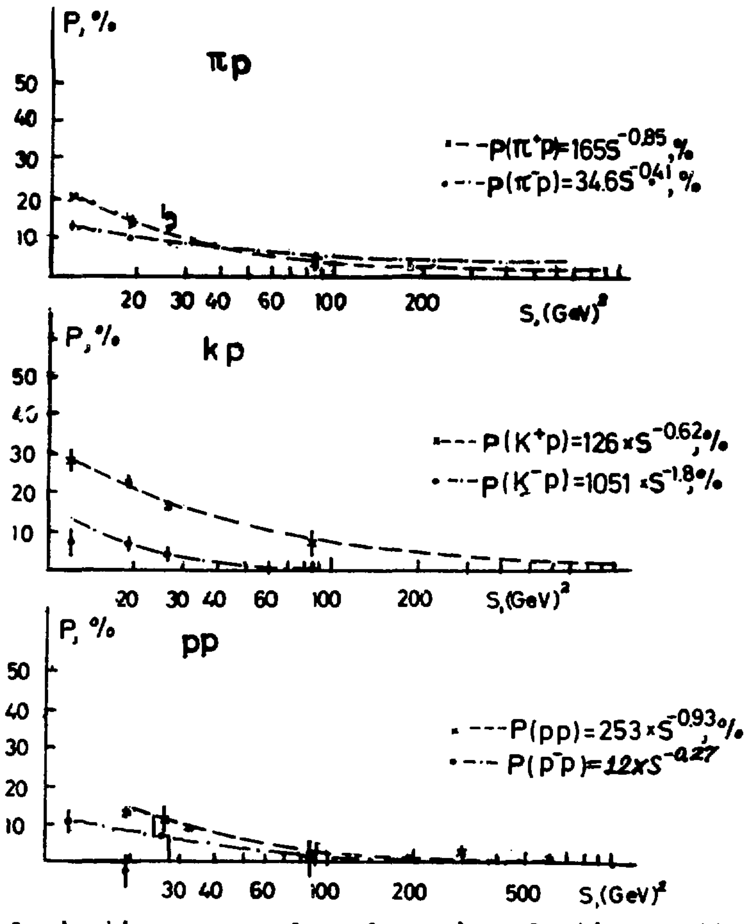


Fig. 2. Polarization energy dependence in elastic scattering at t=-0.2 $(GeV/c)^2$. The data at energies ≤45 GeV were used to fit to the expression choosen.

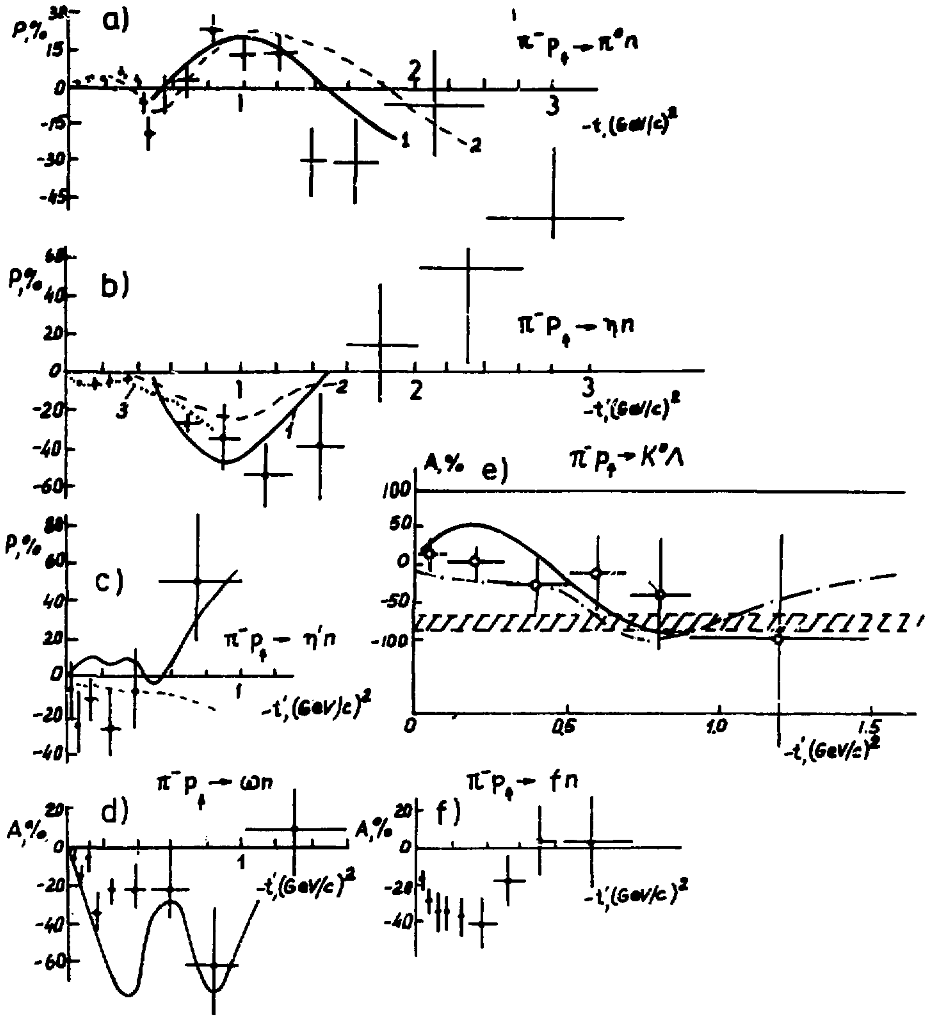
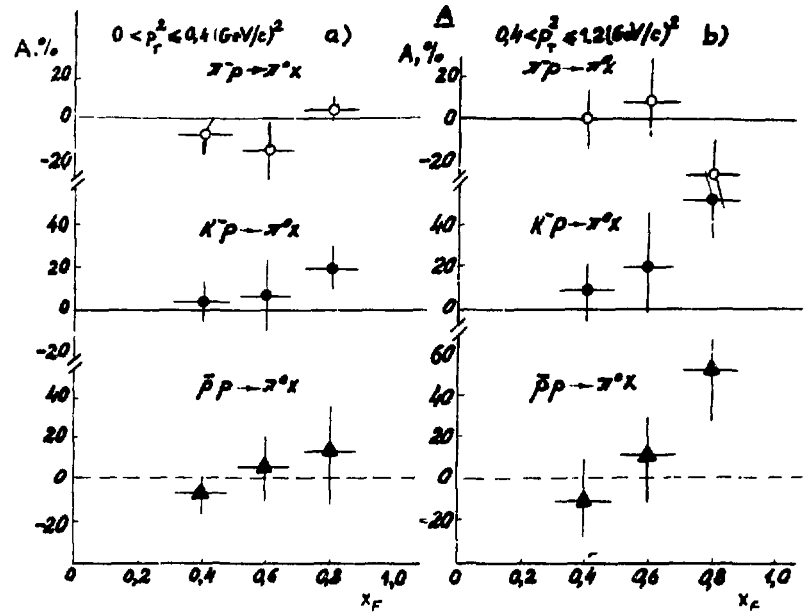


Fig. 3. Asymmetry at initial momentum 40 GeV/c for the following charge exchange binary reactions: a) $\pi^- p \to \pi^0 n$, b) $\pi^- \to \eta n$, c) $\pi^- p \to \eta' n$. d) $\pi^- p \to \omega n$, e) $\pi^- p \to K^0 \Lambda$, f) $\pi^- p \to fn$.

Theoretical results:

a) solid line - quark model in U-matrix approach of Tyurin et al[5]; dashed line - odderon model of E.Leader et al. (Nucl. Phys., 1972. v. B47, p. 445); b) solid line - U-matrix of Troshin et al.: dashedline - Redge model (M.Saleem et al. Prepr. CHEP-P4-112-83, Lahore, 1983); dotted line - Arestov et. al. (Nucl. Phys. (Sov.) 40, 204, 1984); c) solid line - Enkovsky et al.[7]; dashed line - Arestov (Prepr. IHEP, 86-82, Serpukhov, 1986); d) solid line - Achasov et al. (Prepr. TF-53, Novosibirsk, 1984); e) solid line - Arestov et al. (Prepr. IHEP 82-124, Serpukhov, 1983); dash-dotted line - eikonal model calculation (Arakelyan et al. Nucl. Phys. (Sov) 38, 1525, (1983)); shaded area - prediction of Lund model (B.Andersson et al. Prepr. Lund Univ. LUTP 82-6).



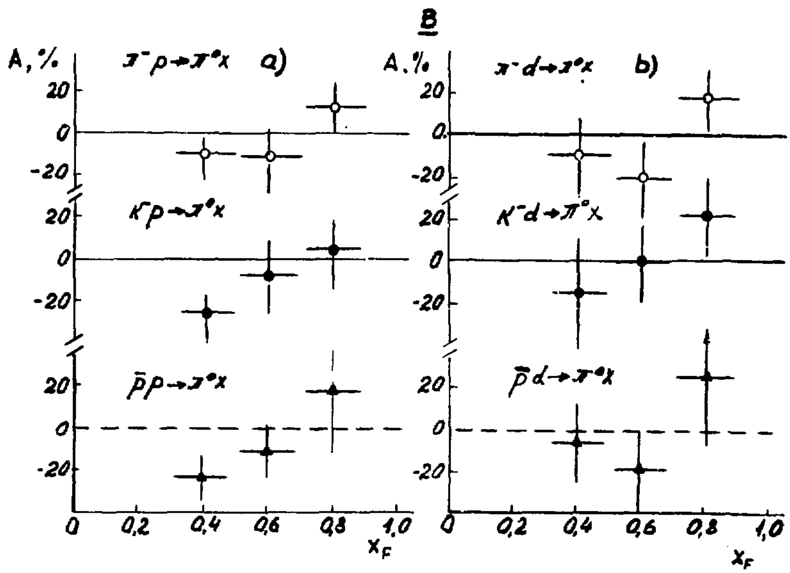


Fig. 4A. X_F-dependence of inclusive π^0 asymmetry in reactions: a) $\pi^- p$, $K^- p$, $\bar{p}p$ at $0 < p_T^2 \leqslant 0.4$ $(GeV/c)^2$; b) $\pi^- p$, $K^- p$, $\bar{p}p$ at $0.4 < p_T^2 \leqslant 1.2$ $(GeV/c)^2$.

Fig. 4B. Integrated over $0 < p_T^2 \leqslant 1.2$ $(GeV/c)^2$ inclusive π^0-asymmetry for reactions: a) $\pi^- p$, $K^- p$, $\bar{p}p$. Dashed line – calculation of Ryskin[14]; b) $\pi^- d$, $K^- d$, $\bar{p}d$.

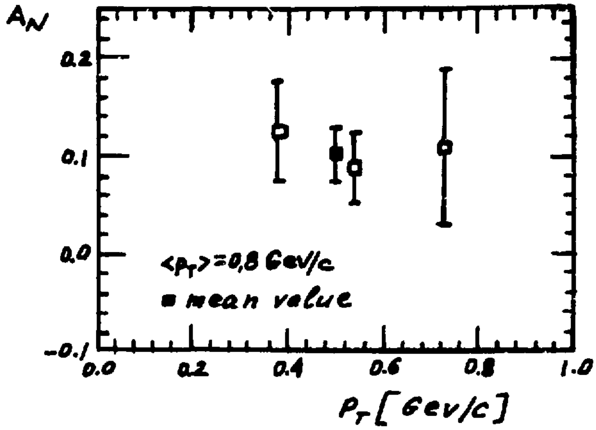


Fig. 5. Asymmetry for reaction $p + p \to \pi^0 + X$ at initial momentum 185 GeV/c[19].

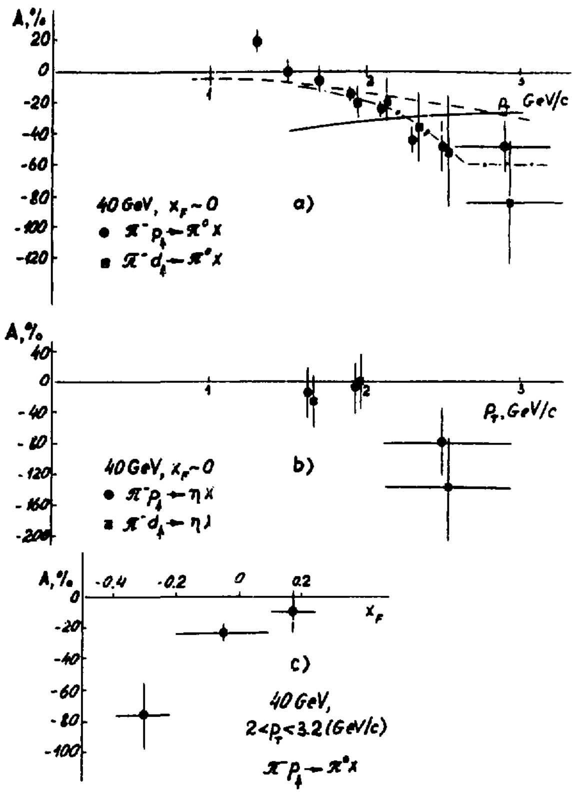


Fig. 6. Asymmetry in the central region for reactions: a) $\pi^- + p \to \pi^0 + X$ –●, $\pi^- + d \to \pi^0 + X$–■. Dashed line is a calculation of Ryskin[14]. Solid line belongs to D.Sivers[15], dashed-doted is of M.Troshin et al.[16]; b) $\pi^- + p \to \eta + X$ – ●, $\pi^- + d \to \eta + X$ – ■; c) X_F-dependence of asymmetry for reaction $\pi^- + p \to \pi^0 + X$ at $2 < p_T < 3.2$ GeV/c.

1. Polarized beams

Today two methods in high energy physics for obtaining polarized proton beams are used: 1) acceleration; 2) the Λ-decay.

Through acceleration one can produce intense and highly polarized beams, but this technique is complicated and expensive. In the second method the expenditures are the same as in the case of producing standard hadron beams, but the intensity is much lower. Nevertheless there are sets of problems which can be solved by applying either first or second technique.

Table 2. Polarized proton beams

Laboratory	Energy (GeV)	Polarization (%)	Intensity (p/sec)	Comments
BNL	13.3 16.5 18.5 22.0	65±3 44±4 47±4 42±4	$8\cdot10^9$	On polarized target $I=3\cdot10^9$ p/s. Technique: acceleration
FNAL	185	45	$3.3\cdot10^5$	Intensity for polarized target position. technique: decay $\Lambda\to p+\pi^-$

In Table 2 the parameters are presented for two beams, used today in experiments at Brookhaven and FNAL. These beams were chosen either because of the highest energy (in the case of acceleration) or for being unique (that is, no similar beams obtained by the same method). The comparison of these beams shows:

- intensities differ by four orders of magnitude;
- polarization is practically the same in both cases;
- to advance in energy is technically easier in the case of secondary beams (from Λ-decay);
- the antiproton polarized beam can be, at present, obtained only by the second method (that is $\bar{\Lambda}\to\bar{p}\pi^+$ or $\bar{\Sigma}^+\to\bar{p}\pi^0$).

With the growth of the accelerator energy main hope relies on the siberian snake technique for conserving polarization, but this technique has not yet been applied to any accelerator.

According to the estimates this method should start working at approximately 70 GeV and higher energies.

2. Polarimeters

Physicists choose the polarimeters taking into account the kind of polarized beams, energy, intensity. One can classify polarimeters as absolute and relative ones. The absolute polarimeters permit to define the value and sign of polarization since they are based on the Coulomb-nuclear interference effect. The relative polarimeters are based mainly on the nuclear reactions with high analyzing power, they allow one to determine the polarization value but not the polarization sign. Nowadays in the E-581 experiment two polarimeters are realized: 1) on the basis of the Coulomb-nuclear interference[20] and 2) on the basis of Primakoff effect[21]. Both polarimeters were used to determine the value and sign of proton and antiproton beam polarization. These polarimeters drawbacks consist in desruption of main measurements during their use.

During the realization of E-581 program at FNAL the asymmetry was measured in the reaction

$$p + p \rightarrow \pi^0 + X,$$

at $\bar{p}_T$=0.7 GeV/c, x_F=0.6. This asymmetry was equal to (10±3)%[12]. This reaction will be used as a relative beam polarization monitor, moreover it appears to be a constructive monitor, that is, it does not desrupt the main run.

Entering into TeV energy range one has to look for new and effective polarimeters.

3. Polarized targets

The following requirements are imposed by physicists upon the polarized targets:

- enriched hydrogen content;
- maximal opening in the useful solid angle;
- maximal polarization;

- polarization homogeneity in the whole target volume;
- minimal polarization built time;
- maximal nuclear spin relaxation time;
- fast polarization reverse;
- radiative resistance;
- adequacy of the main and dummy targets;
- adequacy of the hydrogen target;
- high precision in measuring the polarized target parameters;
- easy maintenances, including automatization.

Besides abovelisted requirements some specific demands arise according to the sort of the beams used (hadron, muon, electron, proton, etc), the type of experiment (total or differential cross-sections, stable particles or resonances, etc.).

Table 3 presents the main features of polarized targets used in the past, at present and to be used in the near future. The first targets on lantan-magnium with 3% hydrogen content were intently omitted.

At first sight one can conclude that, first, a significant progress is made in using materials enriched by hydrogen, secondly, the targets can be classified into three groups according to the sort of particles and third, there are certain tendencies in standartizing the targets. The last statement is important since in view of the progress in the international collaboration it would be useful to make an effective use of the polarized target development in one Laboratory (let us say, in CERN) in another (for example, at IHEP, Serpukhov) or vice versa.

Many of the criteria listed above for the polarized target are under development at different stages, and only the radiative resistant materials have practically been invented almost completely.

The following success in instrumentation can be outlined:

- Saclay physicists have proved[22] that one can produce the polarized target from lithium hydride of large volume, and such target contains three times more hydrogen, than alcohol materials and two times more than in ammonia;

- collaboration of Saclay and CERN physicists was able to reach a fast polarization reverse (30') by using different magnetic fields for building and holding the target polarization[23]. Polarization reverse is achieved by changing the direction of the hol-

Table 3. Polarized Proton Target

Parameters	IHEP (PROZA)	CERN (EMC)	Saclay (NN)	BNL (E-704)	BNL (UM)	ITEP (SPIN)
1. Taget materials	$C_3H_8O_2$	$C_3H_8O_2$	NH_3	$C_3H_8O_2$	NH_3	$C_3H_6O_2$
2. Density ρ, (g/cm^3)	1.1	0.84	1.1	0.84	0.84	1.1
3. Free hydrogen content, (%)	10.6	17.8	10.6	17.8	17.8	10
4. Target dimensions: $x \cdot y \cdot z$, (cm^2)	– 2×20	5×6×38 (2 times) gap:20 cm	2×4.4	3×20	2.9×4	
5. Target polarization, average during runs, (%)						
p(+)	87±3	+82	93±3	–	70±3	75±4
p(–)		–87	–96±3	–	–70±3	75±4
$\bar{p}$					53±3	
6. Useful solid angle						
θ (degree)	15	8	+80,–56	9^o		±20
ϕ (degree)	~300	~360	15	360		~200
7. Polarizing field, (T)	2.1	2.5	2.5	6.5	2.5	2.55
8. Polarization build-up temperature, (K)	0.4	0.4	0.4	0.4	0.5	0.55
9. Polarization build-up time, (h)	2.5					
10. Holding field, (T)	0.45		0.5		2.5	2.55
11. Frozen mode temperature, (K)	0.02		0.035		0.5	0.55
12. Polarization reversal frequency, (h^{-1})	0.05				0.3	0.3
13. Polarization reversal time, (h)	5		0.5		0.5	0.5
14. Cryostat	Hor.Dil.	Hor.Dil.	Ver.Dil.		Contin.	Ver.Cont
15. Polarization relaxation time, (h)						
p(+)	2000		2000			
p(–)	1000		2000			

ding magnetic field and such instrumentation is not acceptable in some cases. Therefore one needs a further progress in this directions;

- CERN physicists have constructed the biggest polarized target for the EMC-team in order to study deep inelastic muon scattering[24];

- JINR physicists proposed to measure the target polarization by implanting the radioactive nuclei into the target substance. The decay anisotropy detection allows one to determine the target temperature, and one can determine the target polarization with a high accuracy[25], knowing the external magnetic fields.

III. THEORETICAL DEVELOPMENTS

Introduction

In perturbative QCD (PQCD) as we know one can make more or less reliable calculations of two spin asymmetries for reactions with two longitudinally polarized particles. Estimate of one spin asymmetry or two spin asymmetry but involving any transverse polarization in initial state leads either to a small effect or to a statement that there is no appropriate scheme of calculation.

Recently a definite break through in one spin asymmetry calculations has appeared (M.Ryskin[14], D.Sivers[15], Troshin and Tyurin[16]). Two spin asymmetries were also recalculated with an account of the recent results of the EMC collaboration on the deep inelastic scattering of polarized muons on polarized protons. In the previous calculations it was assumed that the sea quarks, gluons and orbital moments were not carrying the polarization information. After the EMC experiment this approach was reconsidered. The conclusion is that the asymmetry effects are much bigger than they were expected to be. Some of the experiments, e.g., A_{LL} measurements in prompt photon production has become of first priority, because they allow to reconstruct the function ΔG - spin distribution of gluons in hadrons.

The technique has not yet been well developed for the calculations of the spin transfer reactions, although the first experimental data have already been published ($p_{\uparrow} + p \to \Lambda_{\uparrow}, \Sigma_{\uparrow} + X$).

Below a brief description of these theoretical papers is given.

1. One Spin Reaction

D.Sivers noted[15] that the usual picture of asymmetry in PQCD is intrinsically controversial (earlier similar remark was made by G.Kline et al.), since the coherent and incoherent parts of interaction dynamics were related to the hard parton collisions. But in such interactions asymmetry can not appear because of the absence of the interference between amplitudes with and without spin flips, both amplitudes are real in the Born approximaton. Siver's proposal consists in taking into account the transverse momentum of partons inside hadron, therefore the process transfers the asymmetry into high transverse momenta through the kinematical effects. The final result of his calculation looks like

$$A \cong (Bx_{\perp} + 4)\frac{\varepsilon(x_T)\cdot\mu}{p_T}\,, \qquad (26)$$

where $B\sim10$ is the diffraction slope, $x_T=2p_T/\sqrt{s}$, $\mu^2\sim m^2\sim0.5$ (GeV)^2, ε is a parameter related to the average of parton transverse momenta. The fit to the experimental data gives $\varepsilon \sim 0.1$. After fixing all constants in this expression the asymmetry prediction was made for the reaction

$$p + p \to \pi^{0} + X, \qquad (27)$$

at $\sqrt{s}$=20 GeV, p_T=2÷6 GeV/c and small x_F. Such an experiment should be soon fulfilled at FNAL (E-704) (see Fig.7).

Another conclusion from this model is a statement that in the central region the following relation should be held in general

$$\frac{A_N(h_1 p_{\uparrow} \to \pi X)}{A_N(h_2 p_{\uparrow} \to \pi X)} \cong 1 \qquad (28)$$

and if one can neglect the quark mass in the coherent processes, then

$$\frac{A_N(hp_A \to \pi X)}{A_N(hp_A \to KX)} \cong 1. \qquad (29)$$

If the basic asymmetry $\Delta^N G_{q/p}$ depends upon quark flavour, then in the kinematical region where the valent qq→qq scattering is essential, one can expect the following relation to hold

$$\left.\frac{A_N(hp_A \to p^+X)}{A_N(hp_A \to \pi X)}\right|_{\text{large } p_T} \cong \frac{\langle \Delta^N G_{u/p} \rangle}{\langle \Delta G_{d/p} \rangle}. \qquad (30)$$

As a consequence of isotopic invariance in the whole kinematical region the following expression should be fulfilled

$$\frac{2A_N(hp_A \to \pi^0 X)}{A\ (hp_A \to \pi^+X) + A\ (hp_A \to \pi^-X)} = 1. \qquad (31)$$

These relations can be experimentally checked.

This work, done in the frame of the parton model, shows that QCD can predict significant asymmetries.

The paper/16/ is devoted to the mechanism of asymmetry production in the inclusive hadron yields from a polarized target in the central region. The statement was made that the asymmetry in hadron production was related to the non-zero orbital momentum of $q\bar{q}$ pair. The orbital momentum is caused by the fact that some fraction of nucleon spin is carried by gluons. The observed asymmetry is proportional to the portion of the spin carried by gluons. Therefore, the experimentally measured asymmetry is considered as a manifestation of a gluon component of proton spin. The formula in this model looks like

$$A(s,\ p\ ) = C\left[\frac{88}{\sqrt{s}}\right]^{\alpha} \cdot \beta(p_\perp), \qquad (32)$$

where $\beta(p_\perp) = e^{(p_\perp/m)} \cdot p_\perp^{-k}$ for $p_\perp < p_\perp^0 \simeq 3$ GeV/c.

$$\beta(p_\perp) = \text{const} \quad \text{for} \quad p_\perp > p^0 \qquad (33)$$

In Fig.7 the dash-dotted line shows the results of the calculation according to this expression, in this: m=0.2 GeV, k=8, α>1. It would be interesting to check the asymmetry decrease with energy as it was predicted.

Ryskin[14] proposed a simple model for inclusive asymmetry, using p_T-dependence of the cross section. In this model after collision and exchange by colour gluons (colour exchange) the colour flux tube is stretched between two interacting hadrons. Around this tube the colour magnetic field arises (as around the wire carrying the current), which interacts with the quark colour magnetic moment μ. Interaction energy is $\vec{H}\cdot\vec{\mu}$ since the tube itself is directed along the longitudinal axis, the inhomogeneous chromomagnetic field kicks the quark with the spin-up to the left side and with the spin-down to the right side with a transverse momentum δp_T. As a result the polarized quark receives an additional transverse momentum

$$\delta p_T = H\cdot\mu \simeq \frac{\alpha_s \cdot C_r}{2m_q \cdot 1.6R_c^2} \simeq 100 \text{ MeV}. \qquad (34)$$

Here $m_q \simeq 330$ MeV is the mass of a constituent quark, $R_c = 1/400$ MeV is the distance where the QCD coupling constant α_s varies drastically ($\alpha_s \simeq 1/2$). The asymmetry arising from such interactions is equal to

$$A = \delta p_T \left[\frac{\partial}{\partial p_T}\left(\frac{d\sigma}{d^3p}\right)\right]\cdot\left[\frac{d\sigma}{d^3p}\right]^{-1}, \qquad (35)$$

where $d\sigma/d^3p$ is the inclusive cross section. This formula was applied to two reactions:

1) inclusive hyperon production; then

$P_\Lambda = -0.28X - 0.27P_T + 0.14P_T^2 - 0.02P_T^3$

for $P_T < 1.5$ GeV/c and

$P_\Lambda = -0.12 - 0.28X_F$

for $P_T > 1.5$ GeV/c, that is, polarization P_Λ does not depend upon P_T. These results agree with experimental data.

2) pion production in the central plateau region. The following reaction is under discussion

$$\pi^- + P \rightarrow \pi^0 + X. \qquad (36)$$

The detected π^0 originates either from the fragmentation of polarized quarks scattered at large angle or from any unpolarized parton mainly from gluons. Asymmetry arises only in the first case and becomes

$$A(\pi^0) = A(q)\cdot P(q)/[\sigma(q) + \sigma(g)] = A(q)\cdot P(q)\cdot R, \qquad (37)$$

where $A(q)$ corresponds to elementary subprocess asymmetry, P_q is polarization after the collision, $\sigma(q)$ and $\sigma(g)$ is the π^0 production cross-section from polarized and unpolarized partons, respectively. In the first approximation from SLAC data $P_q = X\cdot A_q$. A_q is calculated with formula (35) at $\delta p_T = 100$ MeV and slope $\partial/\partial q_T \ln(d\sigma/dq^3) = -4.5\ \mathrm{GeV}^{-1}$. To calculate we take the following structure functions

$$\text{valence quarks: } V(x) = 2.8\sqrt{x}(1-x)^2, \qquad (38)$$

$$\text{gluons: } G(x) = 3(1-x)^5, \qquad (39)$$

fragmentation functions:

$$\bar{D}^G \sim (1-z)^2, \qquad (40)$$

$$\bar{D}^q \sim (1-Z). \qquad (41)$$

The fact, that gg cross section is six times larger than the gq one, was taken into account. The fraction of the initial hadron momentum carried by quark at scattering by 90°, is $x \simeq 2q_T/\sqrt{s}$. The results obtained in this model are presented by a dashed line in Fig.6 and are fairly consistent with the measurement results.

The hyperon polarization, particularly, Λ is known to embarrass the theoreticians. Many attempts were made to explain the significant polarization P_Λ, its t and s dependences, but the situation is not satisfactory. In this situation the publication of the paper "Gluon fusion is a source for massive quark polarization" atracted the attention of scientific community. The calculations made in the PQCD frame revealed the following peculiarities (the fixed parameters: $\alpha_s = 0.4$, $m_u = m_d = 0.3$, $m_s = 0.5$, $m_c = 1.5$ and $m_b = 4.5\ \mathrm{GeV}/c^2$):

- angular dependence of s-quark polarization (and other heavy quarks) is antisymmetric around 90° in the c.m.s. of the subprocess;
- maximum polarization P_{max} appears at $\theta \simeq 60^\circ$;
- P_{max} increases with the energy growth and at some point depending on the quark mass (in this particular case, of s-quark

mass) it reaches maximal value and goes down. But this decrease is much slower than the one expectd in the log leading approximation on m/E;

- at fixed momentum scattering angle the polarization increases with the mass growth. For example, at $P_{c.m.}$=13 GeV, $\theta_{c.m.}=60^0$ the following values of P_{max} are predicted:

quarks:	u	s	c	b
P_{max}, (%):	0.5	1.5	3.5	6.

The calculations were done for Λ polarization under assumptions that s-quark combines with (ud) diquark from fast proton, and $x_\Lambda = a + bx_s$ (where a = 0.86, b = 0.7). The asymmetry of s-quark (calculated) is multiplied (enforced) by a factor A=6.3 in order to be consistent with the experimental number, afterwards a good agreement with experimental data is reached (see Fig.8). If all this is correct, then following this model one can predict the expected hyperon polarization for UNK, LHC, SSC.

2. Two Spin Interactions

Briefly we outline in this section the following papers:

1) on $\Delta\sigma_L$ of D.Sivers;

2) on A_{LL} in prompt photon production of E.Berger.

A series of papers published by D.Sivers and his colleagues, is devoted to the theoretical study of $\Delta\sigma_L$(pp) behaviour in the light of new $g_1^p(x)$ measurements at CERN/27/. This function appeared to be very sensitive to the gluon spin distribution ΔG. So at $\sqrt{s}$ = =20 GeV, P_o^2=5 GeV^2 the hard process contribution to $\Delta\sigma_L$(pp) becomes

$$\Delta\sigma^{JET}(pp;\ p\ ,\ \sqrt{s})/_{(\Delta G)} = \begin{cases} 26\ \mu b \text{ at } \Delta G=6 \\ 2\ \mu b \text{ at } \Delta G=0 \end{cases} \tag{42}$$

This observable $\Delta\sigma_L^{JET}$ becomes significant with the energy growth, so at $\sqrt{s}$=100 GeV the estimate leads to

$$\Delta\sigma_L^{JET}(pp;\ p_o,\ \sqrt{s})/_{(\Delta G)} = \begin{cases} 290\ \mu b \text{ at } \Delta G=6, \\ 2\ \mu b \text{ at } \Delta G=0' \end{cases} \tag{43}$$

The number $\Delta G=6$ stems from some estimates using $g_1^p(x)$ data. Before this experiment was done it had been taken to be $\Delta G=0$.

Note, that the soft process contribution to $\Delta\sigma_L$ gets an opposite sign and is bigger in the absolute value than the contribution from the hard process up to p_L=800 GeV/c. At this momentum $\Delta\sigma_L^{SOFT}+\Delta\sigma_L^{JET}=0$. At the momenta higher than 800 GeV $\Delta\sigma_L^{JET}>\Delta\sigma_L^{SOFT}$. Therefore the $\Delta\sigma_L$ measurement on POLEX at UNK at $p_L\simeq$ $\simeq$ 2.5 TeV/c becomes quite acute.

Because of the "spin crisis" problem from the point of view of many theoreticians the $A_{LL}(\gamma)$ measurement in prompt photon production gets a first priority. E.Berger and others[28] in their recent paper made a renewed calculation of prompt photon production in the interaction of longitudinally polarized initial protons. From two possible origins of direct photons: $gq\to\gamma q$ and b) $\bar{q}q\to g\gamma$ the first one dominates at high energy. Then one can write the direct photon production cross section for collisions of unpolarized protons

$$E_\gamma \frac{d\sigma_p}{d^3p_\gamma}(s,\ x_F,\ p_T) \simeq \int dx_a dx_b \left[\frac{F_2(x\ ,\ Q^2)}{x_a} G(x_b,\ Q^2)\ \times \right.$$

$$\left. \times\ E_\gamma \frac{d\hat{\sigma}_{qg}}{d^3p\gamma}(\hat{s},\ x_F,\ p_T) + x_a \longleftrightarrow x_b \right], \qquad (44)$$

$$E_\gamma \frac{d\Delta\sigma_{p\ p}}{d^3p_\gamma}(s,\ x_F,\ p_T) \simeq \int dx_a dx_b \left[2g\ (x_a,\ Q^2)\Delta G(x_b,\ Q^2)\ \times \right.$$

$$\left. \times\ E \frac{d\Delta\sigma_{qg}}{d^3p_\gamma}(\hat{s},\ x_F,\ p_T) + x_a \longleftrightarrow x_b \right]. \qquad (45)$$

Here $F_2(x,\ Q^2)$ and $2g_1(x,\ a^2)$ represent the non-spin or spin structure functions , respectively. They are defined in DIS of leptons on nucleons when both of them are unpolarized or polarized longitudinally. As is seen in the first case the unpolarized cross-section is proportional to the gluon distribution function $G(x_b,\ Q^2)$, in the second case - to the spin function $\Delta G(x_b,\ Q^2)$.

The second case is of particular interest, since the prompt photon production asymmetry gives insight into the gluon spin distributions in the polarized nucleon. Earlier before the EMC experiment was done it has been assumed that $\Delta G=0$, but now the estimate gives $\Delta G=3\div6$. If so, the asymmetry effect should be significant. The estimated cross sections as the function of energy are shown in Fig.9. The solid line represents cross sections forcollisions of unpolarized particles, the dash-dotted line and dashed line correspond to the collisions of polarized particles for two values of the parameter $x_c=0.2$ and 1, respectively. x_c is a boundary for $\Delta G(x, Q_o^2)$ following from the condition

$$\Delta G(x, Q_o^2) = \begin{cases} G(x, Q_o^2), & x_c < x \leq 1 \\ x/x_c G(x, Q_o^2), & 0 \leq x < x_c \end{cases} . \quad (46)$$

At least two conclusions can be made from this Figure: 1) it is benefical to make this experiment at high energies (going from 200 GeV to 1 TeV one can gain one order in the cross section) and 2) the asymmetry is sensitive to the x_c and it varies in the region from 1 to 10%.

3. Spin Transfer

The study of spin transfer from the initial polarized to final particle is very interesting in the following reactions

$$a_i + b \to c_f + d \quad (47)$$

or

$$a_i + b \to c_f + X, \quad (48)$$

where f denotes the final particle whose polarization we measure; i is the initial polarized particle. Let us discuss a more practical case of initial particle polarization P_i normal to the reaction plane and we are interested in the final particle polarization in the same direction. Then

$$\vec{P} = \frac{P_o + D_{nn} P_i}{1 + P_o P_i} \vec{n}. \quad (49)$$

P_o is the final particle C polarization in the case when the initial particle a was not polarized; D_{nn} is the spin transfer parameter. Its value is restricted in the region $-1 \leq D_{nn} \leq 1$. In the high energy region ($\geq$ 5 GeV) this parameter has not been yet measured for binary reactions (47). There are experimental data for the following reactions

$$p_{\uparrow} + p \to \Lambda_{\uparrow}, \Sigma_{\uparrow} + X \tag{50}$$

at the initial momentum of 13 GeV/c [29]. In the measured p_T region this parameter appeared to be zero. Therefore the polarization transfer from proton to Λ, Σ-hyperons is absent. This fact is explainable in the model of T. De Grand and H.Miettinen.

4. Final Particle Polarization

There are caculations of the final particle polarization for the reaction [30]

$$p_{\uparrow} + p \to \gamma_{\uparrow} + X. \tag{51}$$

As we discussed earlier the main contribution to this process is from the compton scattering: $gq \to \gamma q$. The asymmetry in this subprocess is close to one. When going to the real process one should know the polarized and unpolarized proton structure functions. Choosing special functions one can obtain asymmetry shown in Fig.10. The asymmetry effect A_{LL}^{if} varies from 20 up to 100% as the function of x_F in the region 0-1 for the Carlitz-Caur distribution and from 20 to 40% for the SU(6) distribution. The DIS lepton-nucleon experiment favours the first distributon. So this experiment is of great importance for checking QCD. The problem consists in measuring direct photon circular polarization. There are possibilities: 1) birefringence technique (low efficiency) and 2) circular polarization transfer to the electromagnetic shower and measurement of the polarization of the shower leading electrons.

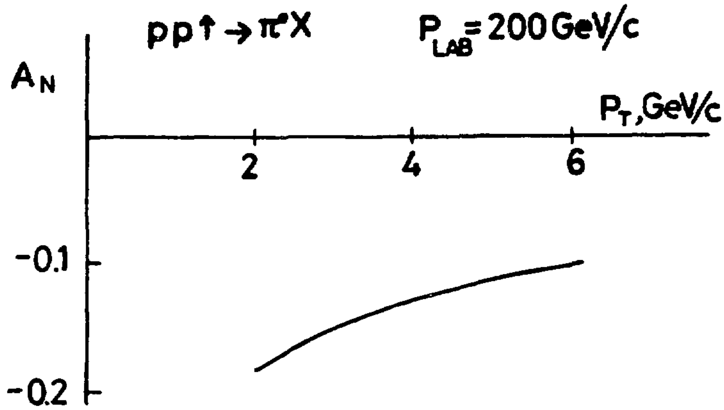


Fig. 7. Asymmetry prediction for reaction p +p→π^0+X at $\sqrt{s}$=20 GeV, X_F= 0, p_T= (2-6) GeV/c[15].

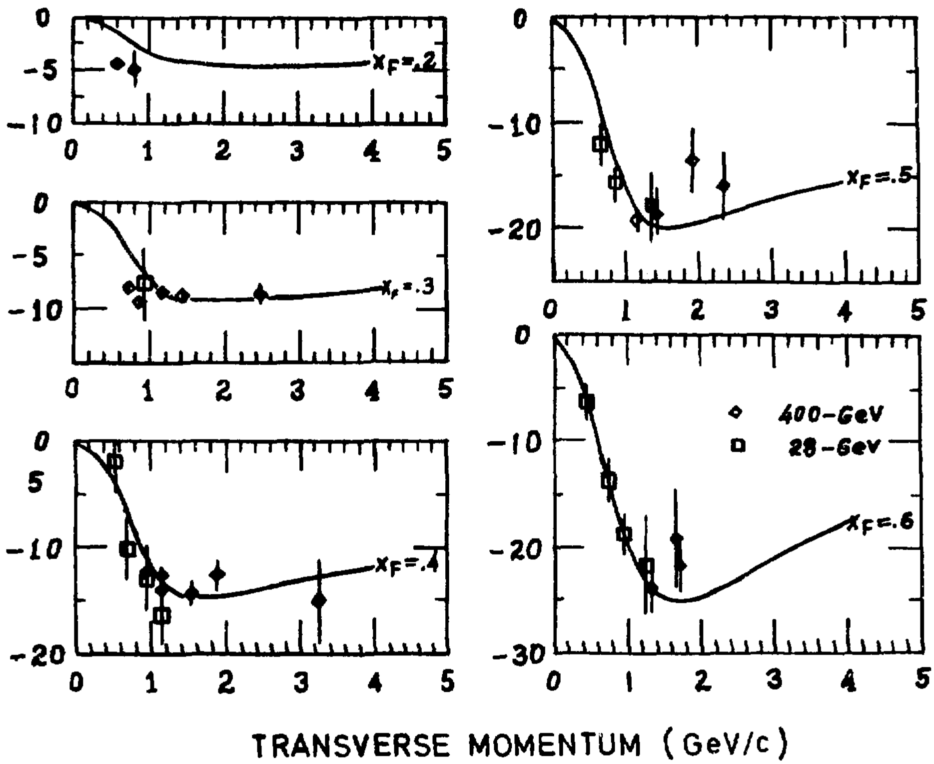


Fig. 8. Hyperon polarization calculation[26] and comparison with experimental data.

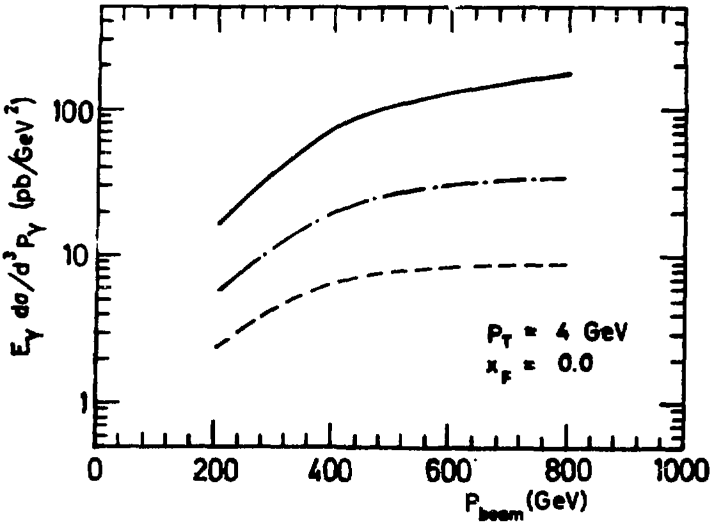


Fig. 9. Predictions for prompt photon production in pp collision at p_T=4 GeV/c and X_F= 0 as function of energy. Solid line corresponds to the unpolarized initial state; dash-dotted and dashed lines - to the difference of cross sections for longitudinally polarized initial particles for two values of X_c=0.2 and X_c=1.0 which enters in function $\Delta G(x_c, Q_0^2, X)$ /28/.

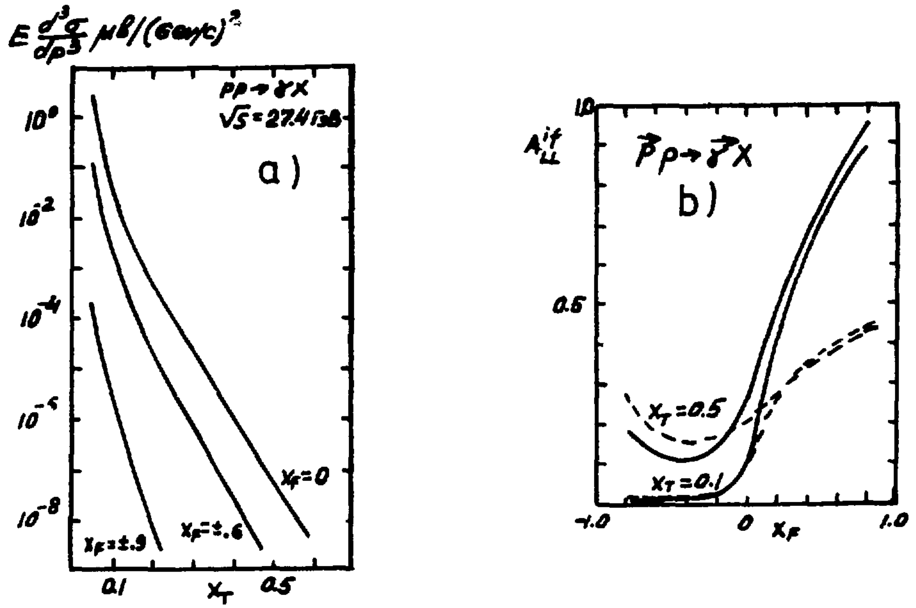


Fig. 10. Calculations of prompt photon production at $\sqrt{s}$=27.4 GeV versus X_T at different X_F /30/: a) prompt photon production cross section for Carlitz-Kaur distribution; b) transferred asymmetry in reaction $p + p \to \gamma + X$ for Carlitz-Kaur distribution (solid line) and conservative SU(6) distribution (dashed line).

IV. PROSPECTS

Introduction

It is obvious for spin physicists that future accelerators should be capable of accelerating polarized beams. For that reason one should finalize R&D for siberian snakes, polarimeters and other necessary items. The collaboration of the teams from different contries will be very useful to reach this goal. The polarization programs at different accelerators need a special discussion and coordination. Such a coordination is desirable so as to obtain the maximal results with minimal physics overlapping and evidently spending minimal resources. It would be natural in this line the involvement of the whole or a large part of E-704 collaboration in to POLEX program at UNK. In this case the experience and resources of E-704 in POLEX (stuff and specialists) may be used very effectively. There is no doubt that one can have many similar examples.

Contacts and joint work of theorticians on polarization program with the view to solve the main and urgent problems like the "spin crisis" problem, would be very encouraging.

1. Experiments

At present two experimental proposals have been submitted to measure the structure function $g_1^p(x)$ with high precision and to measure $g_1^n(x)$ for the first time. One experiment[31] is done with the EMC equipment with a new polarized target (two halves cf 60 cm each with a 30 cm gap; $\varnothing$=4-5 cm; P_T=80±30%, butanol), with a new magnetic system for the polarization build up and reverse and with muon polarimeter. The beam energy is E=100 GeV, $I=2\ 10^7$ p sec^{-1}, P_μ=80±5%. The second experiment at LEPP[32] is planned to scatter polarized electrons on a polarized jet target. At the first stage the electron beam energy will be of 23 GeV, at the second stage - 50 GeV. In table 4 the comparison is made of the parameters of these two experiments. It is seen that DIS μp experiment has prevailing advantages over the ep scattering at LEPP using the jet target.

Table 4. Comparison of two experiments planned to measure spin structure functions

Parameters		SMC	LEPP			
Beam		μ		e		
Energy, GeV		100		23, 50		
Polarization, %		80±3		60		
L, $s^{-1} \times cm^{-2}$		2×10^{31}		2×10^{29}		
Start, Y		1991		?		
Statistics		for 220 days	for 1 year (?)			
x	$\langle Q^2\rangle$ $(GeV)^2$	N(p) (in 10^6 ev.)	x	$\langle Q^2\rangle$ (GeV^2)	N(p)	σ(p)
00.1-0.02	2.3	1.42	0.010-0.015	1.48	2295	0.0205
0.02-0.03	3.0	1.78	0.015-0.024	1.77	3112	0.0218
0.03-0.04	4.0	1.59	0.024-0.037	2.11	3852	0.0242
0.04-0.06	5.3	2.68	0.036-0.056	2.49	4584	0.0275
0.06-0.10	6.9	3.74	0.056-0.087	3.32	4115	0.0328
0.10-0.15	8.6	2.89	0.087-0.133	4.83	3132	0.0398
0.15-0.20	10.1	1.60	0.133-0.205	7.03	2123	0.0507
0.20-0.30	12.0	1.67	0.205-0.316	10.26	1264	0.0712
0.30-0.40	15.0	0.64	0.316-0.487	14.79	571	0.1122
0.40-0.70	19.7	0.64	0.487-0.750	22.39	128	0.2451
Statistical errors						
		ΔA_1^p				
	x=0.015	0.018				
	x=0.55	0.087				
		ΔA_1^n				
	x=0.015	0.037				
	x=0.55	0.314				

For the prospects of the polarization physics one should also outline the following experiments:

- A_N and A_{LL} measurements in direct photon production in E-704 program[33]. Attainable region of p_T up to 5 GeV/c, precision in ΔA_N= 2-4% and ΔA_{LL}= 2-8%;

- A_N measurements in inclusive π^0, Λ and Σ, $\pi^{\pm}$ productions; π^0 production occurs in the central region, other reactions in the fragmentation region of polarized beam; incident momentum is 185 GeV (E-704);

- $\Delta\sigma_L(pp)$ and $\Delta\sigma_L(p\bar{p})$ measurements at 185 GeV (E-704);

- NEPTUN experiment at UNK with an ultracold polarized target[34]. At the first stage the elastic pp-scattering polarization will be studied up to $p^2<10\ (GeV/c)^2$ (NEPTUN-A); at the second stage the π^o, Λ, charged hadron and direct photon productions will be measured;

- POLEX experiment using a variety of polarized beams: p , $\bar{p}$, n , γ , e , μ , Y[35]. As a first rank experiment one plans to measure $\Delta\sigma_L$, $\Delta\sigma_T$, prompt photons, dileptons (including $\bar{c}c$ production), hyperons. The Collaboration is big and strong enough (E-704 collaboration might join POLEX at UNK) in order to fulfil the simultaneous measurements of several observables using the E-704 experience;

- physicists are pushing the program of accelerating the polarized beam at IHEP (U-70, UNK), at FNAL (new 150 GeV injector, Tevatron), at VLEPP (500+500 GeV at the first stage, 1000+1000 GeV at the second stage). These works are extremelly important for the prospects of the polarization studies at high energies.

2. Instrumentation

At present the instrumentation is developing (or should) in the following directions:

- design of new polarized beams. In POLEX program it is foreseen to produce besides p and $\tilde{p}$ beams the polarized neutron beams (n and $\bar{n}$), hyperon beams Y ($\bar{Y}$), lepton, γ and muon beams $\mu^{\pm}$;

- polarimeters in the TeV region;

- the sources of polarized p and $\bar{p}$ beams with high intensity permitting to reach the level of unpolarized beam intensity;

- jet polarized targets with high density;

- acceleration of polarized proton (antiproton) beams up to TeV and higher energies;

- the use of bent crystals to produce the high energy polarized beams, to measure the magnetic moments of short living particles (heavy quarks);

- polarized target with 100% hydrogen content (or free nucleons) as an ideal goal;

- the polarized target magnetic system with large useful solid angle (4π ideally).

3. The prospects of theoretical study

From the experimentator point of view the efforts of theoreticians could fall into the following lines:

- explanation of data already existing;

formulation of a set of "full experiments" in order to solve the spin crisis problem. For example, what experiments, at what energies and kinematical regions one should do in order to separate each parton contribution to nucleon spin;

-planning of experiments on big accelerators.

It would be very important if theoreticians could indicate the high priority polarization experiments at Tevatron, UNK, LHC and SSC with their justifications. Experimentators could estimate their reliability. In any case the aim should be deep and systematic tests of QCD.

V. SUMMARY

Usually in Summary talk the results obtained are listed, the prospects are outlined and the hopes are expressed to obtain new important results to the next workshope.

I would like to stress another thing. In high energy physics the "polarized" community of physicists is getting its shape. This community marked by unity, welldefined goal puts much effort to reach a day when each new accelerator will foresee from the beginning the acceleration of polarized beams, and the high energy physics spin study will keep a leading position. Let me wish a success to such a community.

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