TOWARDS THE SOLUTION OF THE NUCLEON SPIN PROBLEM *

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Experimental confirmation of the nucleon quark structure is usually identified with the results of MIT-SLAC inelastic scattering program [1]. In particular, measurements of the cross-sections for the deep inelastic scattering (DIS) of electrons:

$$e + p \longrightarrow e' + X$$

allowed to study a matter granularity of the order of $\lambda < 0.5$ fermis. From very beginnig DIS of polarized leptons off polarized protons was recognized as an excellent tool for studying of the internal spin structure of nucleons [2]. Already the first studies of the deep inelastic scattering (DIS) of polarized leptons off polarized protons (EMC/CERN and SLAC/Stanford, 1987-88) have shown, that an amount of the proton spin carried by quarks is surprisingly small. This phenomenon was named "the proton spin crisis". In this lecture the present status of this subject is reviewed. After an introduction to the polarized DIS, the experimental aspects of the proton spin crisis are discussed. Then, some theoretical explanations of this phenomenon are listed. Recent progress in the obtaining polarized particles inside the storage rings as well as development of the polarized internal gas targets made possible to start new generation of experiments. Two such projects using polarized electrons, namely HERMES and SLAC E-143 as well as the proposed studies of the polarized $p + p$ DIS in the storage ring RHIC are presented. Some ideas about future extensions of such experiments are also discussed. Many facts concerning the subject were learned by the author during his participation in FILTEX/HERMES projects in Heidelberg. Therefore, all members of this group are warmly acknowledged for many discussions of the problems raised in this lecture.

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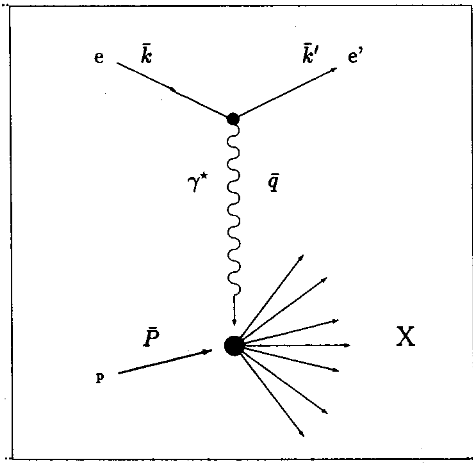
1. Polarized DIS and the spin structure

1.1. DIS kinematics

The lowest order Feynman graph and kinematical variables commonly used in lepton-nucleon DIS are shown in figure.



$$Q^2 = -q^2 = | k - k' |^2 ,$$
$$Q^2 \approx 4EE' \sin^2 \left(\frac{\theta}{2}\right) ,$$
$$\nu = \frac{PQ}{M} = E - E' ,$$
$$x = \frac{Q^2}{2M\nu} \qquad (0.0 \le x \le 1.0) .$$

In the inclusive e–N deep inelastic scattering energies E and E' and the scattering angle θ are measured, from which the 4-momentum transfer Q and electron energy loss ν are calculated. Alternatively, the Bjorken scaling variable x is often used.

1.2. Cross-sections [3]

The differential cross-sections in lepton–nucleon DIS induced by unpolarized particles can be expressed in terms of two phenomenological functions $F_1(Q^2, x)$ and $F_2(Q^2, x)$. These functions contain all dynamics of the process and they can be found studying the dependence of the cross-section on the energies E and E' and the scatering angle θ.

$$\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow} = \frac{8\alpha^2 E'}{Q^2} \left\{ \sin^2\left(\frac{\theta}{2}\right) \frac{F_1(Q^2,x)}{M} + \cos^2\left(\frac{\theta}{2}\right) \frac{F_2(Q^2,x)}{\nu} \right\} .$$

Similarly, the spin-dependent parts of the cross sections depend on two phenomenological structure functions G_1 and G_2 as follows:

$$\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow} = \frac{4\alpha^2 E'}{Q^2} \{ (E + E' \cos\theta) M G_1(Q^2, x) - Q^2 G_2(Q^2, x) \} ,$$
$$\sigma^{\uparrow\rightarrow} - \sigma^{\uparrow\leftarrow} = \frac{4\alpha^2 E'}{Q^2 E} E' \sin\theta \{ M G_1(Q^2, x) - 2E G_2(Q^2, x) \} ,$$

for the longitudinally and transversally polarized target, rspectively. Thus, in the case when both, the incident leptons and target nucleons, are polarized longitudinally the corresponding experimental spin assymetry can be approximately expressed as $A_{LL}(x) = G_1(x)/F_1(x)$. Quite often instead of these, another functions: $g_1 = M^2\nu G_1$ and $g_2 = M\nu^2 G_2$ are used.

1.3. Simple picture of unpolarized and polarized DIS

If the target nucleon is built of a number of identical pointlike partons we are dealing with the feature of scaling. Then, all the structure functions $F_i(Q^2, x)$ and $G_i(Q^2, x)$ become in the limit of large Q^2 the functions of x only.

Considering the Feynman graph for the interaction of the virtual photon with an individual quark in the target nucleon there are three important rules, valid for massless quarks and large Q^2:

- Measured experimentally Bjorken variable x is equal to that part of the linear momentum of the target nucleon which is carried by the interacting quark.
- Virtual photon is polarized along the helicity of the incident electron.
- Virtual photon can interact only with those quarks which possess helicity opposite to that of the photon. Thus, the incident electron interacts only with quarks of opposite helicities, independently on the helicity of the target proton.

1.4. Partons in nucleons and quark distribution functions

In real nucleon we have following kinds of partons:

- valence quarks: proton = (u^v, u^v, d^v); neutron = (d^v, d^v, u^v)
- Dirac "sea" quarks: $(u, \bar{u}), (d, \bar{d}), (s, \bar{s})$ and $(c, \bar{c})$. The last, "charmed" quarks are often neglected.
- gluons

We define spin the averaged quark distribution function $q_f(Q^2, x)$ as the probability of finding a quark with flavour f ($f = u, d$ or s) with the momentum xP in the target nucleon having the momentum P. Then, $F_1(Q^2, x) \approx \frac{1}{2}\Sigma_f e_f^2 q_f(Q^2, x)$. Analogously, the spin-dependent quark distribution functions $q_f^+(Q^2, x)$ describe quarks with helicity parallel to that of the target nucleon and $q_f^-(Q^2, x)$ describe quarks with the opposite helicity. In terms of these functions:

$$g_1(Q^2, x) \approx \tfrac{1}{2}\Sigma_f e_f^2 \Delta q_f(x, Q^2)$$

and

$$I_p(Q^2) \approx \int dx g_1(Q^2, x) = \tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s\,,$$

where $\Delta q_f = q_f^+ - q_f^-$.

1.5. Nucleon spin content

In terms of the integral quantities Δu, Δd and Δs we can define the following linear combinations, which could be measured experimentally:

$$\Delta u - \Delta d = \frac{G_A}{G_V} \qquad \text{measured in neutron } \beta\text{-decay},$$

$$\Delta d - \Delta s = G^{\Sigma n} \qquad \text{measured in hyperon decays},$$

$$\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s = I_p \qquad \text{measured in polarized lepton DIS}.$$

From this system of three linear equations one can find all quantities Δq_f separately and the contribution to the proton spin carried by all quarks:

$$\Sigma = \Delta u + \Delta d + \Delta s = 2\langle S_z \rangle .$$

The total proton spin can be expressed as:

$$\tfrac{1}{2} = \tfrac{1}{2}\Sigma + \Delta G + \Delta L_z ,$$

where ΔG labels gluon contribution and ΔL_z those of the orbital angular momentum. An analogous formula is valid for a neutron.

2. Measurements of the nucleon spin structure functions

2.1. First measurements of SLAC/Stanford and EMC/CERN. The "proton spin crisis".

First measurements of the structure functions $g_1^p(x)$ were performed for *ep* (SLAC [4]) and μp (EMC/CERN [5]) in the range $0.01 < x < 0.7$. SLAC E-80 and E-130 experiments used 20 GeV external polarized electron beam ($\langle Q^2 \rangle = 2$ GeV^2) and polarized proton target (frozen buthanole). In EMC/CERN, 200 GeV external polarized muon beam was used together with polarized frozen ammonia target. From these data the following values of the Δq_f can be extracted [6]:

	"$\Delta s = 0$"	"$\Delta s \neq 0$"	n QPM	rel QPM
Δu /2	0.348	0.375	$\frac{4}{6}$	0.46
Δd /2	−0.280	−0.254	$-\frac{1}{6}$	−0.16
Δs /2	0.000	−0.113	0.0	0.0
$\langle S_z \rangle$	0.0068 (14%)	0.006 (1%)	$\frac{1}{2}$	0.32

In the first column of the Table values of $\Delta q_f/2$ are displayed for the case when the contribution from "sea" s quarks is set to zero. In the second column all three values of Δq_f were treated as free and calculated using the method shown above. Thus, the total quark contribution to the proton spin appeared to be very small (14 % or 1 %), in comparison with values predicted in the simplest version of the non-relativistic quark parton model ("n QPM") as well as in its relativistic version ("rel QPM"). Just these surprising results have got the name of the "proton spin crisis".

2.2. New data from SMC/CERN and SLAC. First measurements of $g_1(x)$ for the neutron.

In new CERN experiments started last year by Spin Muon Collaboration (SMC) polarized muons are scattered off the polarized deuteron target made of frozen deuterated ammonia [7]. Up to now measured are values of $g_1^n(x) + g_1^p(x)$ at muon energy 200 GeV for $\langle Q^2\rangle = 5$ GeV^2.

In SLAC $E-142$ experiment [8] performed at electron energy $E_{el} = 20$ GeV for $\langle Q^2\rangle = 5$ GeV^2 a polarized gas, laser pumped ^{3}He target was used. The reason is, that ^{3}He represents almost pure neutron polarized target, as the two protons almost always have opposite helicities, so that their contributions to the target spin cancel.

Both experiments are still running and only the first, non-complete data are available, but they were already analyzed by Close and Roberts [9].

3. What does the Theorist say?

Whole problem can be divided as follows:

- **Reliability and consistency of the data.**
  According to Close and Roberts [9] a $\langle Q^2\rangle$ dependence of the $F_1(Q^2)$ and thus the $\langle Q^2\rangle$ dependence of the measured spin assymetry A_{LL} cannot be ignored. Practically, it means that improved new experimental data on $F_1(Q^2, x)$ should be used in the evaluation of the $A_{LL}(Q^2, x)$. Also, experimental values of $g_1(x)$ should be correctly extrapolated to the lowest not measured, as yet, region of $x < 0.01$ using, say, a Regge approximation.
  Similarly, the $g_1(x)$ values for large $x > 0.6$ can be better approximated by the values calculated within the valence quark model "VQM", because the experimental values in this region are still very poor. Consistently, all set of data including those for proton, neutron and deuteron should be analyzed simultaneously. Also, an extra Q^2 dependence of the structure functions due to the so called "higher-twist" contributions can be included.

As a result, one can conclude by now that the discreapancy of the experimental $g_1(x)$ and calculated in the "VQM" are not so big for "hard" quarks in the nucleon ($x > 0.6$) and the whole problem of the "spin crisis" concerns the soft part of the distribution function, only.
However, some signifficant inconsitencies still remain unsolved. It is believed, that they reflect more fundamental physical problems.

- **Spin structure function $g_1(x)$.**
The discreapancy of the experimental values of $g_1^p(x)$ and those calculated within simple quark models is usually prescribed to the spontaneous breaking of the chiral symmetry in the nucleon [10]. If one defines the following new linear combinations of the Δq_f: $a_3 = \Delta u - \Delta d$ and $a_8 = \Delta u + \Delta d - 2\Delta s$ then it appears, that the experimental values of a_3 and a_8 agree with theoretical ones within about 30%. This is a measure of the octet axial vector current non-conservation. On the other hand, for the quantity $a_0 = \Delta u + \Delta d + \Delta s$, which is a measure of the non-conservation of the singlet axial vector current, this discreapancy is about 8–10 times! Within PQCD this is attributed to the existence of the "triangle anomaly" in the singlet channel, represented by the triangle graph of the interaction of the gluon with the singlet axial vector current. Such interpretation leads to the following formula for the "effective" quark contribution to the nucleon spin:

$$\widetilde{\Sigma} = \Sigma - \mathrm{const}\,\Delta G\,,$$

where ΔG represents an extra contribution from gluon polarization.
Unfortunately, such theory does not give us unique values of ΔG and Δs. It is however possible, that this problem can be solved within the non-perturbative QCD [11], where the effect is prescribed to the interaction of the instantons (specific fluctuations of the QDC vacuum) with quarks in the nucleon. As a result, a strongly polarized cloud of the sea quarks appears, which effectively screens the spin of the original quark.

- **Transversal spin structure function $g_2(x)$.**
This function was found to contain two parts: the first, a "trivial" one, which is fully expressed by known longitudinal function g_1 and the second one, denoted as $\tilde{g}_2$, which have contributions from the "Twist-3" operators [12]. Thus, measuring both the g_1 and g_2 functions one can experimentally find higher-twist contributions.

- **Other spin structure functions** (not observed in the $e + p$ DIS).
Complete analysis of the problem of spin structure functions leads to some functions which cannot observed in polarized lepton–nucleon DIS. However, they can be measured in other processes. These new functions are:

- **"Chirality-odd" functions** [13, 14].
  They are observed, for example, in polarized $pp \longrightarrow l^+l^- + X$ Drell–Yan process.
- **"Higher-twist"** structure functions [14].
- Target spin-1 (deuteron) functions $b_1(x)$ and $\Delta(x)$ [15, 16].
  They can be measured in unpolarized electron + aligned deuteron DIS. These functions vanish if the deuteron contain bound neutron, proton and pions, only, and they are non-zero if a nontrivial part of the wavefunction exists, mixing partons from different bound nucleons.
- **Higher multipole structure functions** [17], observed for deformed targets (*e.g.* ^{7}Li or ^{165}Ho).

4. New challenge for Experimentalists: the use of storage rings.

The general idea of new generation experiments is to use polarized particles accelerated in storage rings together with polarized gas internal targets (PIT's). In the last few years very important steps were done in this direction. They are described below.

- **Highly polarized electron beam at HERA**
  In electron storage rings the beam became spontaneously polarized due to the effect of the spin-flip synchrotron radiation, provided that the ring is flat and perfect. However, in rings at some characteristic energies exist strong depolarization effects. Therefore, obtaining a high degree of the beam polarization is, in fact, a very difficult task. Last autumn the beam polarization of about 60% have been reported at HERA [18].
- **Highly polarized hydrogen gas targets in Novosibirsk and Heidelberg**
  The idea of polarized gas internal target was given by Haeberli [19] and first devices have been constructed in Novosibirsk [20] and Heidelberg [21]. Such target is, in fact, a combination of a standard polarized atomic beam source based on the Stern–Gerlach principle (supplemented by the RF transition cells increasing the population of the desired magnetic substates), with the windowless storage cell of a special shape. Thus, the highly polarized atomic gas jet is further strongly compressed in the area of the interaction with the beam. Due to the special coating material of the cell and the additional guiding magnetic field, this compression takes place without a signifficant loss of the target polarization.
  Such highly polarized deuterium target was first constructed in Novosibirsk and tested in their storage ring VEPP with 2 GeV electrons [20]. In Heidelberg the first polarized hydrogen target was constructed and

installed in the storage ring TSR [21]. It was tested with 27 MeV α-beam stored in the ring by means of the elastic α-p scattering. The recent results were: about 90% of the proton polarization and about 10^{14} atoms/cm^2 of the effective target thickness [22]. The last device keeps, at present, the world record in its class and meets all conditions necessary for its use in high energy storage rings.

- **Towards highly polarized ^{3}He gas internal target.**
  People from Caltech [23] and Princeton [24] used optical pumping of the ^{3}He gas by the laser light to produce highly polarized gas. A combination of this principle with the storage cell technique can provide an effective Helium target for storage rings.
- **The "Siberian snake" works!**
  In proton cyclic accelerators the effect of the spontaneous polarization of the beam is negligibly small, so that initially polarized particles must be accelerated to high energies. During acceleration they must pass many depolarizing resonances without a signifficant loss of the polarization. To avoid a strong depolarization close to these resonances special measures has to be undertaken. One, very important, is to make quick spin-flips of the beam when such resonance is reached. The "Siberian snake" is just such spin-flipping system of magnets. Such device, although theoretically known for years, only very recently was constructed and tested at the proton storage ring in Bloomington/Indiana [25].

5. New big projects

At present there exist a number of big projects, which plan to disentangle the puzzle of the nucleon spin. Three of them I would consider as the most important. They are:

- **HERMES**: (DESY, MPI-Heidelberg, Caltech *etc.*) [26]. Deep inelastic scattering of polarized electrons off polarized targets at HERA/DESY. Longitudinally polarized 30 GeV electrons from HERA storage ring. Longitudinally or transversely polarized internal gas target: Hydrogen, Deuterium and ^{3}He. To be measured: Spin structure functions $g_1(x)$ and $g_2(x)$ both for protons and neutrons and deuteron spin structure functions $\Delta(x)$ and $b_1(x)$.
- **SLAC E-143:**
  Deep inelastic scattering of 50 GeV polarized electrons. Polarized ^{3}He external target [27]. Measured with a high accuracy $g_1(x)$ function for neutrons and, at least preliminary results for neutron $g_2(x)$.
- **Polarized protons at RHIC:**
  In the further future very attractive looks also a perspective of obtaining polarized protons at RHIC/BNL and subsequent studies of pp DIS and

other more specific processes [28]. These studies can give a direct answer on the gluonic contribution to the nucleon spin ΔG as well as to measure "chirality-odd" spin structure functions.

6. Future perspectives

Projects listed above, after being completed, will probably exhaust possibilities offered by studying the problem of the nucleon spin by means of the inclusive deep inelastic scattering of polarized particles. Further progress can be made if one use some semi-inclusive or exclusive processes. There is already a big list of such processes, which were analysed teoretically and can be used for further studies. In particular, except already mentioned measurements of ΔG and "chirality-odd" structure functions by means of polarized pp collisions, one can measure separately Δu , Δd and Δs contributions as well as Δu^v and Δd^v values for valence quarks, only.

Often, the only thing what is needed is to develop detecting systems, which will discriminate between various particular processes. As an example, we can take the analysis of Veltri [29] who discussed further extension of HERMES project enabling measurements of valence quarks spin functions by means of $e + p = \pi + e' + X$ and $e + p = K + e' + X$ reactions.

There are also some new possibilities opened by the use of new targets. This is certainly the case of the deformed target nuclei, such as ^{7}Li or ^{165}Ho [30]. The use of aligned targets of deformed nuclei make possible to measure higher multipole spin structure functions.

In this context, it is worthwhile to mention that for years in Heidelberg and in Marburg was very succesfully developed technique of obtaining polarized atomic beams of ^{6,7}Li and ^{23}Na with freely chosen rank of the polarization tensor, and even obtaining the atomic beam in pure magnetic substates [31] . This technique offer a possibility to construct suitable gas targets for storage rings and, in the future, to perform very interesting experiments from the border-line of particle and nuclear physics.

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