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ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА. ТЕОРИЯ

SINGLE SPIN ASYMMETRIES IN HIGH ENERGY REACTIONS AND NONPERTURBATIVE QCD EFFECTS

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We discuss some experimental and theoretical results on single spin asymmetries (SSA) in high energy lepton–hadron and hadron–hadron reactions. In particular, recent results on meson SSA obtained by HERMES are considered in detail. We also discuss the SSA results obtained recently by COMPASS, as well as those from BRAHMS, PHENIX and STAR. Special attention is paid to a possible nonperturbative QCD mechanism that might be responsible for the observed meson SSA. This mechanism originates from the spin-flip quark–gluon chromomagnetic interaction induced by the complex topological structure of the QCD vacuum. We argue that in semi-inclusive deep-inelastic scattering a large SSA is expected not only for mesons but also for baryons due to strong nonperturbative final state interactions between ud-diquark and u-quark in the fragmenting proton.

Обсуждаются некоторые экспериментальные и теоретические результаты по односпиновым асимметриям (ОСА) в лептон-адронных и адрон-адронных процесссах при высоких энергиях. В частности, подробно рассмотрены недавние результаты коллаборации HERMES по ОСА мезонов. Мы также обсуждаем последние результаты по ОСА коллабораций COMPASS, BRAHMS, PHENIX и STAR. Особое внимание уделено возможному непертурбативному механизму, который мог бы быть ответственным за возникновение наблюдаемых мезонных ОСА. Этот механизм связан с кварк-глюонным хромомагнитным взаимодействием, переворачивающим спин, и возникает за счет сложной топологической структуры вакуума КХД. Мы также приводим аргументы, что в полуинклюзивном глубоконеупругом рассеянии большие ОСА ожидаются не только для мезонов, но и для барионов за счет непертурбативного взаимодействия в конечном состоянии между ud-дикварком и u-кварком в фрагментирующем протоне.

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INTRODUCTION

The spin structure of the nucleon remains a very intriguing topic. In spite of tremendous experimental and theoretical efforts in the last twenty years, yet there is no clear understanding of the spin structure of the nucleon based on fundamental QCD theory (see, e.g., the

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recent review [1]). One promising way to progress in understanding the spin structure of the nucleon is to study various single spin asymmetries (SSA) in inclusive meson production in lepton–hadron and hadron–hadron interactions [2, 3]. At present, several experiments are producing very important results on SSA in high energy reactions. In particular, the HERMES Collaboration at DESY has observed significant asymmetries in pion electroproduction on both longitudinally [4] and transversely polarized proton targets [5, 6]. Furthermore, recently HERMES also announced preliminary data on the observation of a very large SSA for K^+ [6]. These data support the idea that SSA do not vanish in the high energy limit $\sqrt{s} \gg \Lambda_{\rm QCD}$, in contrast to the expectation of the naive perturbative QCD (pQCD) approach $A_N \propto \alpha_s m_q/\sqrt{s} \ll 1$, in which SSA should be suppressed by both the small value of the QCD coupling constant α_s and the small current quark mass m_q [7]. We recall that SSA at high energy and large transverse momenta were also found in inclusive and exclusive hadron production in hadron–hadron collisions a long time ago [8,9]. At present, the investigations of SSA in hadron–hadron collisions are continued by STAR, PHENIX and BRAHMS at RHIC using very large energies [10, 11].

In this paper we will discuss experimental results and indicate a possible explanation of large observed SSA within the nonperturbative QCD approach.

1. SSA RESULTS IN SIDIS

The main tool to study the mechanism of SSA in QCD using lepton–nucleon scattering is the measurement of SSA for π and K meson inclusive electroproduction off a polarized nucleon target, i.e., semi-inclusive deep-inelastic scattering (SIDIS). The HERMES Collaboration [12] was using the polarized 25.7 GeV e^+/e^- beam of HERA, which was scattered on a polarized proton target. The SSA measurements at HERMES are devoted to the extraction of information on the so-called Sivers distribution and Collins fragmentation functions which are appearing in the leading twist approach to SSA based on perturbative QCD (pQCD) factorization [2, 3]. These functions carry important information on the structure of strong interactions at large distances and can be calculated only within nonperturbative QCD. Fortunately, in SIDIS on a transversely polarized target there is the possibility to separate the effects of these two functions because they induce two distinct angular dependences. The SSA for a transversely polarized target,

$$A^h_{UT}(\phi,\phi_s) = \frac{1}{\mid S_\perp \mid}\frac{N_h^\uparrow(\phi,\phi_s) - N_h^\downarrow(\phi,\phi_s)}{N_h^\uparrow(\phi,\phi_s) + N_h^\downarrow(\phi,\phi_s)} \tag{1}$$

receives contributions from Sivers

$$A^{\rm Siv}_{UT}(\phi,\phi_s) \propto \sin(\phi - \phi_s) \tag{2}$$

and Collins

$$A^{\rm Col}_{UT}(\phi,\phi_s) \propto \sin(\phi + \phi_s) \tag{3}$$

asymmetries which are proportional to the corresponding Sivers and Collins functions, respectively. The definition of angles used in (1), (2) and (3) is shown in Fig. 1. The kinematic range of the HERMES experiment for the SIDIS reaction

$$e(k) + P(P) \to e(k') + h(P_h) + X(P_X) \tag{4}$$

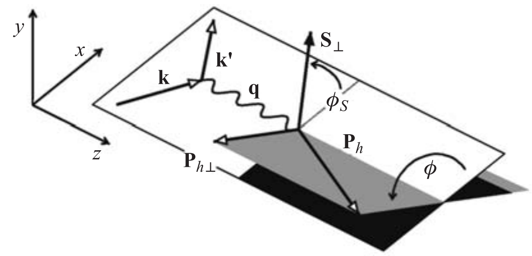

Fig. 1. Polarized SIDIS kinematics

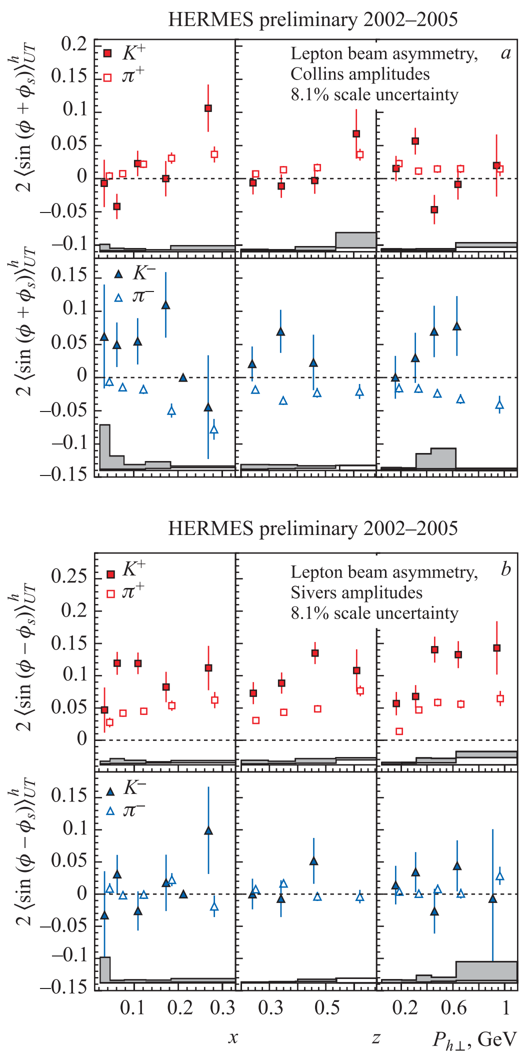

Fig. 2. Collins (a) and Sivers (b) amplitudes for charged kaons (closed symbols, as labelled) and charged pions (open symbols, as labelled) as a function of x, z and $P_{h\perp}$

is as follows:

$$W^2 > 10\ \text{GeV}^2,\quad Q^2 > 1\ \text{GeV}^2,$$
$$0.1 < y < 0.85,\quad 0.2 < z < 0.7, \tag{5}$$

where

$$W^2 = (P+q)^2,\quad Q^2 = -q^2 = -(k-k')^2,$$
$$y = \frac{P\cdot q}{P\cdot k},\quad z = \frac{P\cdot P_h}{P\cdot q}. \tag{6}$$

The average value of the Bjorken variable $x = Q^2/(2P\cdot q)$ for the HERMES SSA measurement is rather large: $\langle x\rangle = 0.09$. The average value of the proton polarization was $S_T = 0.78 \pm 0.04$. In Fig. 2 HERMES data on the Collins and Sivers asymmetries are presented.

The first main feature of the HERMES data is a large Collins and a small Sivers asymmetries for negatively charged particles. The second observation is a very large K^+ Sivers asymmetry. This asymmetry is bigger than the π^+ asymmetry by approximately a factor of three. Such an anomalous K^+ asymmetry is very difficult to explain in the naive pQCD factorization approach to SSA, in which the main contribution to both K^+ and π^+ SSA is coming from valence u-quark fragmentation.

Recently, first results on SSA in SIDIS for π and K mesons produced by scattering of positively charged muons with momentum 160 GeV/c off a deuteron target [13], and for positively and negatively charged particles off a proton target [14], were presented by the COMPASS Collaboration [15]. The main difference compared to the HERMES kinematics is the much smaller value of x, in the range $0.008{-}0.02$. One of the unexpected results obtained by COMPASS is that practically all SSA in SIDIS are compatible with zero, with the exception of an indication of a nonzero Collins asymmetry on the proton for both negative and positive hadrons at $x > 0.05$. A possible explanation for the difference in the observed SSA between HERMES and COMPASS is the rather different kinematic region of SIDIS explored by them.

2. SSA IN HADRON–HADRON INTERACTIONS

Additional information about the mechanism of SSA is coming from inclusive particle production in hadron–hadron interactions. Unfortunately, in this case it is impossible to separate the Sivers and Collins asymmetries because no information is available about the parton scattering plane.

In this situation, one way to describe SSA in hadron–hadron scattering is using as input the Sivers and Collins functions which were extracted from fits to SIDIS data [16]. However, this procedure is based on several strong assumptions. One of them is the assumption about the validity of factorization in the description of SSA. Moreover, the mechanisms of SSA in SIDIS and hadron–hadron scattering might be different (see discussion below). One evidence here is that SSA in hadron–hadron scattering practically do not show any energy dependence (Fig. 3), in contrast to SIDIS, where there are rather large differences in the SSA results obtained by HERMES and COMPASS. We would also like to point out that hadron–hadron data on SSA

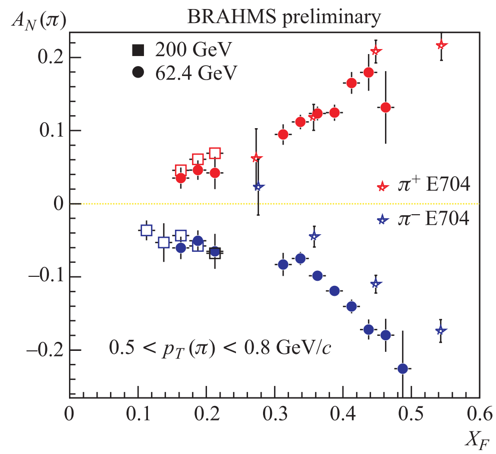

Fig. 3. Comparison of charged pion asymmetries measured at 200 and 62.4 GeV by BRAHMS [11] and at 19.4 GeV by E704 [8]

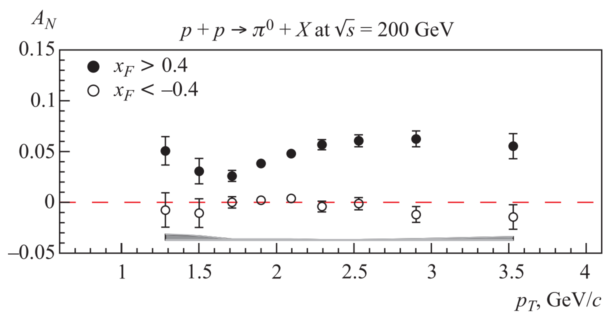

Fig. 4. STAR experiment SSA data at $\sqrt{s} = 200$ GeV for neutral pions as a function of $P_{h\perp}$ [10]

in elastic reactions [9] show some strong oscillations as a function of $P_{h\perp}$. Some evidence for such oscillations one can also see in Fig. 4, where the recent STAR data on SSA for neutral pion production are presented [10]. Such a behavior has never been observed in SIDIS, and therefore cannot be described by using the Sivers and Collins functions extracted from SIDIS data.

3. NONPERTURBATIVE QUARK–GLUON INTERACTION AS A SOURCE OF SSA IN HIGH ENERGY REACTIONS

As was mentioned in Introduction, even assuming factorization it is necessary to use some nonperturbative input to describe SSA. There are several calculations of the Sivers function which include nonperturbative dynamics in different ways. The first estimate of this function was obtained within the MIT bag model [17]. Recently, a calculation of the Sivers function was performed within the Isgur–Karl model [18]. However, we emphasize that these models can be used only for some qualitative estimates because they are based on the assumption of the dominance of perturbative gluon exchange between struck and spectator quarks. It is very hard to expect the validity of such an assumption for transverse momenta $p_\perp \leqslant 1$ GeV. In this approach, nonperturbative effects in SSA have the scale $p_\perp \approx 1/R_{\rm conf} \approx \Lambda_{\rm QCD}$ and are related only to confinement dynamics, but they are not included in the interaction between struck and spectator quarks. In this respect, the final-state interaction mechanism for SSA considered in [19] also belongs to the above class of models.

The model of the nonperturbative QCD vacuum based on strong topological fluctuations of gluon fields called instantons is one of the most successful models for nonperturbative QCD effects (see the review [20]). It has been shown that additionally to the famous multiquark 'tHooft interaction, which gives rise to a negative sea quark polarization in the proton [21], instantons also lead to *spin-flip quark–gluon chromomagnetic interactions*, which should have strong effects to SSA in high energy reactions [22] (see also the recent discussion in [23] and [24]). The effect of including such an interaction,

$$\mathcal{L}_{\mathcal{I}}{}^{\rm chromo} = -i\frac{g_s\mu_a}{2m_q^*}\bar{q}\sigma_{\mu\nu}t^aG^a_{\mu\nu}q, \qquad (7)$$

where μ_a is the quark anomalous chromomagnetic moment, on the Sivers function was considered in [25]. This contribution is arising from the interference of the diagrams presented in Fig. 5.

It was shown that this contribution is very large [25] and not suppressed by powers of the strong coupling constant. The specific flavour dependence of the instanton contribution leads to a large negative contribution to the u-quark Sivers function. Furthermore, it also leads to a small Sivers function for the d-quark. This is in qualitative agreement with the HERMES result on a large Sivers asymmetry for positively charged pions and a small one for negatively charged pions (see Fig. 2). For a more detailed comparison with data one should additionally include the contribution to SSA originating from the final state interaction (FSI) induced by nonperturbative quark exchange between struck and spectator quarks (Fig. 6) [26].

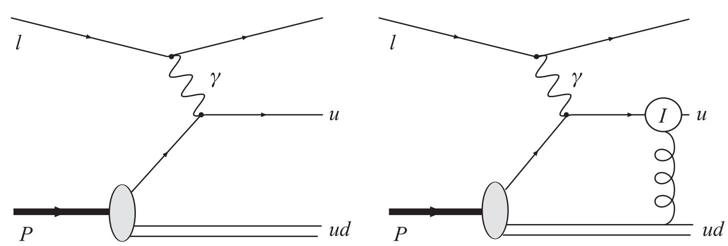

Fig. 5. The diagrams giving rise to SSA in SIDIS. The symbol I denotes the instanton

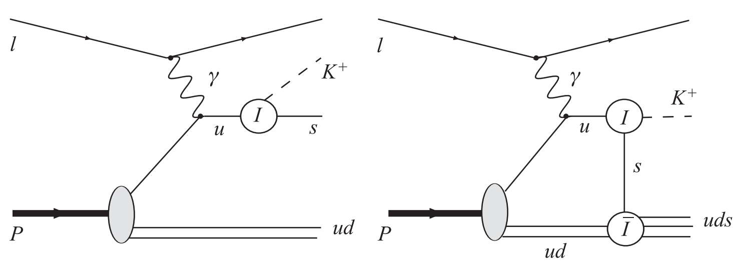

Fig. 6. The quark-exchange FSI contributing to K^+ SSA in SIDIS

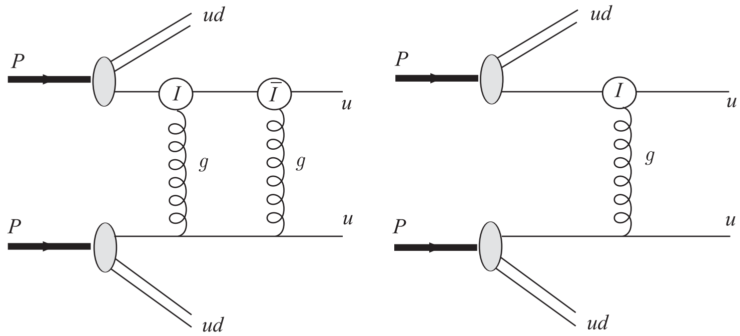

Fig. 7. The diagrams which lead to nonzero SSA in hadron–hadron interaction

Finally, we emphasize that in fact the mechanisms leading to large SSA in SIDIS as presented in Fig. 5 and for hadron–hadron interactions [22] might be different, especially in the small $p_\perp$ region. As an example, in Fig. 7 we present the diagrams which might be responsible for SSA in hadron–hadron reactions (such a two-gluon exchange is subleading in SIDIS).

4. SSA FOR BARYONS IN SIDIS

The mechanism that might be responsible for large observed SSA for different types of hyperons is one of the long-standing problems in strong interactions [27, 28]. In particular, a very large SSA for Λ hyperons was observed with both polarized and unpolarized hadron beams. Recently, a large SSA for neutrons at large x_F was observed by the PHENIX Collaboration [29] at $\sqrt{s} = 200$ GeV. Such a large asymmetry is very difficult to explain in the conventional Regge approach [30]. We point out that the FSI between u-quark and ud-diquark depicted in Fig. 5 should lead not only to a SSA for the meson coming from u-quark fragmentation, but also to a SSA for baryons to which a ud-diquark should mainly fragment. Indeed, in general, on the quark level the u-quark SSA in SIDIS is proportional to

$$A^u = A e_{\mu\nu\rho\sigma} S_\mu p_\nu q_\rho k_u, \tag{8}$$

where A is some function of dynamical variables; S is the proton spin, and p, q and k_u are the momenta of proton, photon and u-quark, respectively. Due to conservation of total momentum one has

$$p + q = k_u + k_{ud}, \tag{9}$$

where k_{ud} is the ud-diquark momentum, and therefore the asymmetry for a ud-diquark should be opposite in sign to the u-quark asymmetry:

$$A^{ud} = -A e_{\mu\nu\rho\sigma} S_\mu p_\nu q_\rho k_{ud}. \tag{10}$$

From Eqs. (8) and (10) it follows that one should expect a strong correlation between SSA for mesons and baryons which are fragmenting from u-quark and ud-diquark, respectively. For example, in the case of scalar ud-diquark dominance in the proton wave function, we predict for the Sivers asymmetry in SIDIS for directly produced Λ hyperons and neutrons[1]:

$$A^{\rm Siv}(\Lambda) \approx -A^{\rm Siv}(K^+), \tag{11}$$

$$A^{\rm Siv}(\text{neutron}) \approx -A^{\rm Siv}(\pi^+). \tag{12}$$

In principle, such baryon asymmetries are hence expected to be large at HERMES kinematics because the experimental values for K^+ and π^+ Sivers SSA measured by HERMES are quite large [4–6]. The predictions in Eqs. (11), (12) are mainly based on momentum conservation, and therefore quite general with a weak dependence on the FSI model used.

Due to large statistics for Λ hyperons collected by HERMES and COMPASS, there may be a real possibility to check our prediction in Eq. (11) in SIDIS for a transversely polarized target. For the spin-zero ud-diquark the Collins asymmetry for baryons is expected to be zero because this asymmetry is related to the correlation between the spin of the fragmenting quark system and the momentum of the resulting secondary particles. We also mention that it is difficult to predict the SSA for the outgoing proton in the SIDIS reaction $e+p \to p+X$ because it is well known that at large x_F a large contribution to the inclusive cross section is coming from diffractive excitation of the proton. This contribution is expected to dilute the SSA for the final proton.

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