Instantons and Spin-Flavor effects in Hadron Physics

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Abstract

We discuss the role of instantons in the spectroscopy of ordinary and exotic hadrons as well as in high energy reactions. We argue that the instanton induced flavor- and spin-dependent quark-quark and quark-gluon interactions can explain many features of the hadron spectrum. The observed anomalous spin and flavor effects in various reactions with hadrons can also be understood within the instanton model for QCD vacuum.

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1 Introduction

The existence of instanton, a strong nonperturbative fluctuation of gluon fields, in the QCD vacuum is considered as a primary factor of chiral and $U(1)_A$ symmetry violations (see reviews [1, 2]). A well-known example of an instanton induced interaction is the famous t’Hooft quark-quark interaction, which can be obtained from the consideration of the so-called quark zero-modes in the instanton field [3]. Another example for the instanton induced chirality-flip interaction is the non-perturbative quark-gluon chromomagnetic interaction [1, 2]. In this Letter we discuss the effects of these interactions in the hadron spectroscopy and reactions with hadrons. Our main purpose is to stress the importance of the instanton induced quark-quark and quark-gluon interactions in the spin and flavor structure of hadrons and in high energy reactions in a few GeV region for momentum transfer.

2 Instanton induced interaction and structure of ordinary and exotic hadrons

Recently, the evidence for the existence of the exotic $\Theta^+$ pentaquark state with the strangeness $S = +1$ has been obtained. In spite of the unclear experimental status of this state at the present time, the fundamental question about the existence of bound multiquarks has not receive a certain answer so far. This is the reason why the search for quark exotic states is included in many experimental programs at current and planned facilities. Such experimental activity calls for the reconsideration of old theoretical approaches to the multiquark spectroscopy which was based on the assumption of the dominance of a perturbative one-gluon exchange between quarks inside the bag [5]. Within such an approach, the correlations between quarks in the bag are very weak and, therefore, one expects that multiquarks should have rather large masses and widths. Furthermore, the bag model predicts a very large number of these states which should mix with each other as well as with the colorless hadronic resonances carrying the same quantum numbers.

The first hint at the possibility to have a light pentaquark with a small width was found within the soliton model for baryons [6]. In this model the peculiarities in the structure of pentaquarks are determined by the collective dynamics of quarks in the background of the meson field. The explanation of a small mass and width of the pentaquark was also given within the constituent quark model based on the possible cluster structure of the pentaquark arising from the attraction in some diquark state due to the perturbative one-gluon exchange (OGE) between quarks [7].

In the alternative approach to the hadron spectroscopy, in which nonperturbative, instanton induced interaction between constituent quarks plays dominant role, was developed in [8] (see a recent review [9]). In this model, many features of the observed spectrum of ordinary hadrons can be described by the contribution arised from the effec-
tive two-body and three-body t’Hooft interactions:

\[
H^{(2)}_{\text{eff}}(r) = -V_2 \sum_{i \neq j} \frac{1}{m_i m_j} \bar{q}_i R(r) q_i L(r) \bar{q}_j R(r) q_j L(r) \left[ 1 + \frac{3}{32} (\lambda^a_i \lambda^a_j) 
+ \frac{9}{32} (\sigma_i \cdot \sigma_j \lambda^a_i \lambda^a_j) \right] + (R \leftrightarrow L),
\]

(1)

where \( m_i = m_i^{\text{cur}} + m^* \) is the effective quark mass in the nonperturbative vacuum. In particular, such an interaction helps solving the famous \( U(1)_A \) problem, which is related to the large mass of \( \eta' \) meson and, simultaneously, produces a very light \( \pi \) meson state. It is well known that it is extremely difficult to obtain a heavy \( \eta' \) and a light \( \pi \) meson within the OGE model. Furthermore, the instanton based constituent quark model has been used to calculate the properties of various tetraquark states and to study the structure of the \( 2\Lambda \), so-called H-dibaryon, state. In comparison with the OGE models quite a different spectrum of mass of multiquarks was obtained \[10\], \[11\].

For multiquark hadrons with open and hidden strangeness and for the reactions including the strange quark the three-body t’Hooft interaction

\[
H^{(3)}_{\text{eff}}(r) = -V_3 \prod_{i=\text{u,d,s}} \bar{q}_i R(r) q_i L(r) \left[ 1 + \frac{3}{32} (\lambda^a_i \lambda^a_d + \text{perm.}) 
+ \frac{9}{32} (\sigma_u \cdot \sigma_d \lambda^a_u \lambda^a_d + \text{perm.}) - \frac{9}{320} d^{abc} \lambda^a \lambda^b \lambda^c (1 - 3 (\sigma_u \cdot \sigma_d + \text{perm.})) 
- \frac{9}{64} f^{abc} \lambda^a \lambda^b \lambda^c (\sigma_u \times \sigma_d) \cdot \sigma_s \right] + (R \leftrightarrow L),
\]

(2)

might also be important.

Recently, this model has been applied to the pentaquark spectroscopy \[12\], \[13\]. It was argued that a specific flavor- and spin-dependent t’Hooft multiquark interaction forms a certain type of two- and three-particle clusters inside the multiquark hadron. As the result, the bound multiquark states might appear in the instanton field. The importance of the instantons in the multiquark dynamics was confirmed by direct calculation of the light pentaquark and tetraquark masses within the QCD sum rules in \[14\], \[15\], \[16\].

We should mention that the possibility of the scalar ud-diquark formation inside the nucleon due to the instanton interaction was also discussed in \[20\] and within the QCD sum rule approach (QCDSR) in \[18\], \[17\]. Furthermore, the QCDSR calculation carried out in \[13\] confirms the conclusion of the constituent model \[12\] about the appearance of the light ud\bar{s} triquark state in the instanton field. Instantons also play a very important role in glueball physics \[20\], \[21\] and, in particular, are responsible for mass splitting of the parity partners in the glueball sector \[22\], \[23\]. Finally, we should emphasize that the instanton induced multiquark interaction also gives rise to some weak hadronic decays and, particularly, can be considered as a fundamental QCD mechanism for the empirical \( \Delta I = 1/2 \) rule found in the weak \( \Delta S = 1 \) decays \[19\].
3 Spin and flavor structure of nucleon

More than fifteen years ago we argued that an instanton induced spin-flip interaction should lead to negative polarization of sea quarks inside polarized nucleon and to valence quark depolarization [24, 25]. In this type of approach, it is not necessary to have a sizeable gluon polarization to explain the famous "spin crises" [26]. The recent results obtained by the STAR [27] and COMPASS Collaborations [28] give a small value of gluon polarization and, therefore, confirm our prediction. Furthermore, we showed [24, 29] that due to the Pauli principle for quarks in the instanton field, large sea quark polarization should also be accommodated by large flavor asymmetry in the proton sea. Indeed, this $\bar{u} - \bar{d}$ asymmetry was found in the Drell-Yan muon pair production from analyses of the cross section of pp and pn scatterings [30, 31].

4 Instanton effects in high energy reactions

The significant single-spin asymmetries (SSA) in meson production in semi-inclusive deep-inelastic scattering (SIDIS) observed by the HERMES Collaboration at DESY [32, 33] is the challenge for the pQCD approach to spin effects in strong interactions. One of the unexpected phenomena found by HERMES is the large Sivers asymmetry for the $K^+$ meson. Such asymmetry is in contradiction with expectations of the naive pQCD based on the picture in which the main contribution to $K^+$ SSA comes from u-valence quark fragmentation [34]. Recently, a new approach to the SSA in SIDIS has been suggested [35]. It is based on the instanton induced final state arising from multiquark interaction (Eq.2).

![Figure 1: The diagrams contributing to $K^+$ SSA. The symbol I denotes the instanton (antiinstanton).](image1)

![Figure 2: The dependence of $K^+$ Sivers asymmetry on $p_\perp$ in the comparison with preliminary HERMES data [33].](image2)
the large $K^+$-meson Sivers asymmetry. For more detailed comparison with the data one should take into account form factors in the nonperturbative $s$-(ud) and $s$-u vertices.

![Diagram](image_url)

Figure 3: The quark chromomagnetic moment contribution to the high energy quark-quark scattering.

Instantons can also contribute to the quark-quark, quark-gluon and gluon-gluon scattering at high energy. It is well known that the t-channel gluon exchange leads to a nonzero contribution in the high energy partonic cross section. There are two possible contributions to gluonic exchange arising from instantons. One of them contributes to the gluon propagator and determines its infrared behavior. The other is related to the nonperturbative correction to the quark-gluon vertex and can be treated as a quark chromomagnetic moment induced by instantons

$$L_{\text{chromo}}^{\text{chromo}} = -i \frac{g_s \mu_a}{2 m_i^2} \bar{q} \sigma_{\mu \nu} t^a G_{\mu \nu}^a q,$$

(3)

where $\mu_a$ is the quark anomalous chromomagnetic moment, $G_{\mu \nu}$ is the gluon field strength. For the off-shell gluon with virtuality $q$ the instanton induced quark-gluon vertex, Eq. (3), should be multiplied by the instanton form factor

$$F(z) = \frac{4}{z^2} - 2K_2(z),$$

(4)

where $z = q \rho_c / 2$ and $\rho_c$ is the average size of instanton in the QCD vacuum. The value of the quark anomalous chromomagnetic moment is proportional to the instanton packing fraction $f = n_c \pi^2 \rho_c^4 \approx 0.1$ in the QCD vacuum, where $n_c$ is the instanton density. A remarkable property of this new quark-gluon interaction is its chirality structure. Indeed, it leads to spin-flip of quark and, therefore, it might be responsible for large spin asymmetries observed in high energy reactions. Recently, it was shown that the contribution of this interaction to the quark-quark high energy scattering cross section arising from the diagram presented in Fig.1 exceeds the pQCD one-gluon exchange contribution in the region of transverse momentum $p_\perp < 3$ GeV. So one can expect the appearance of the perturbative QCD regime only at a large enough value of $p_\perp$.
5 Conclusion

We discussed the effects of the nonperturbative structure of the QCD vacuum in the strong interaction. It is shown that specific instanton induced interactions between hadron constituents play a very important role in the spectroscopy of ordinary and exotic hadrons as well as in high energy reactions.

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