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Author(s): A. Blotz, Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
E. Shuryak, SUNY Stony Brook, Stony Brook, NY 11794, USA

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The Quark and Meson Structure in the Instanton Liquid Model*

A. Blotz  
*Theoretical Division, LANL, Los Alamos, NM 87545

E. Shuryak  
SUNY Stony Brook, Stony Brook, NY 11794

Abstract

Within an instanton based model of QCD we address the important question of how much of the proton spin is carried by the spins of the quarks and how much is due to orbital angular momentum and the spins of the gluons. Since this question arises already on the level of a single quark inside the proton, we study the axial vector correlation function as well as the anomaly correlator for quarks in the so called Random Instanton Liquid Model (RILM) as well as for the Interacting Instanton Liquid Model (IILM).

Introduction

Recent lattice calculations support the decade old picture of a ground state of QCD which is filled with a liquid of instantons and anti-instantons. These classical solutions of Euclidean field equations do not only describe the qualitative features of low energy QCD but also quantitatively a large variety of hadronic and gluonic two-point correlation functions[1]. As a first step to investigate the structure of the hadrons we have calculated the three point correlation function of the pion with an external electro-magnetic field[2]. The result was not only the reproduction of the monopole shape formfactor but showed also very nicely that the formfactor of the pion is basically the formfactor of the instanton. Hereby the experimentally measured formfactor confirmed an average instanton size $\bar{\rho} \approx 0.35$ fm, which is the value used for more than a decade now[3].

Based on this successful model we are asking now where 'the proton really gets its spin'[4]. For this aim we calculate three point correlation function for the axial vector current in coordinate space and project onto the axial vector coupling as well as the induced pseudoscalar coupling constant[5]. To confirm the finding we also evaluate the divergence of the axial current, which, in the chiral limit, is given by the anomaly.

The quark propagator

The propagator of a single quark in the Instanton Liquid Model is shown in Fig. 1 in dependence of the quark separation $x$ and for the spin flip and spin non-flip amplitude. Both curves are normalized to the free spin non-flip amplitude, so that the short distance behaviour of the spin non-flip amplitude reflects asymptotic freedom. The figure shows a fit with a constant constituent quark mass (cqm), where the quark mass turns out to be $\approx 220$ MeV, but it neither describes the shorter distances $<1$ fm nor the larger ones. A reliable fit is obtained by assuming a momentum dependent quark mass. For small momenta then, the mass corresponds roughly to the constituent quark mass $\approx 360 - 370$ MeV, whereas for larger momenta it approaches zero.

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Fig. 1: The two-point correlation function of a quark, normalized to the free correlator and for the streamline configuration (IILM). The instanton density is $n = 1\text{fm}^{-4}$ [5]. The parameters of the fitting function are $m_1[\text{MeV}], \rho[\text{fm}], m_2[\text{MeV}]$ are given in the legend. Fits with a constant constituent quark mass ($\text{cqm 220}$) are also shown.

The pion electro-magnetic correlator

When considering three-point correlation functions, the coupling of the charged pions to an external electro-magnetic current is not only one of the simplest but is also known to receive large contributions from instantons. As a result of the calculation one can see in Fig.2 that the pion size is strongly dependent on the average instanton size. Taking the experimental error bars on the pion size into account the constraints on the instanton size sharply concentrate around $0.35\text{fm}$. This is the value used for more than a decade now[3].

The axial vector correlator

In order to investigate the spin structure of fermions in QCD one should calculate the three-point function of the fermion and an external axial vector current. In addition to the space-time variables, one has now to choose a certain geometry for the spin of the fermion and the component of the axial current. This allows to obtain independent correlators for the axial vector coupling constant, $g_A^{(0)}$, and the induced pseudoscalar coupling $g_P^{(0)}$. In Fig. 3 the correlation function for the axial vector coupling constant is shown for the streamline configuration and shows a strong suppression ($\approx 35\%$) of $g_A^{(0)}$ compared to the case of the non-relativistic quark model, which gives $g_A^{(0)} = 1$. The mass of the dipole formfactor comes out to be $\simeq 0.5\text{GeV}$, however inclusion of strangeness in the disconnected contribution, which would be necessary to reproduce the $\eta, \eta'$ system, seems to enhance this value while leaving the formfactor at $g^2 = 0$, the coupling constant, rather unaffected.
Fig. 2: The inverse mass of the monopole parametrization of the electromagnetic formfactor of the pion, which is proportional to its mean square radius, is shown in dependence of the instanton size for the RILM configuration. Dashed lines are experimental error bars on the pion size.

Fig. 3: The three-point correlation function $\Pi_{2\gamma}(x,y)$ of a single quark, normalized to the free correlator and for the streamline configuration (IILM). The parameters of the formfactor $g_A, m_A$ are given in the legend for the connected and connected and disconnected contribution.
The divergence of the axial correlator

Using the momentum dependent quark propagator one can the axial vector coupling $g_A$ not only from axial vector current correlator [5] but also from the anomaly. This is because the divergence of the flavor singlet axial current in QCD is non-vanishing in the chiral limit due to

$$\partial_\mu j_{\mu,5}^G(x) = 2m\bar{q}\gamma_5 q + \frac{N_f}{16\pi^2}G_{\mu\nu}G_{\mu\nu}$$

(1)

In Fig. 4 we have evaluated the anomaly term $G_{\mu\nu}G_{\mu\nu}$ as well as the connected and disconnected contribution to $\bar{q}\gamma_5 q$ for a constituent quark. As can be seen the anomaly term (GG disc) for three quark flavours dominates and the disconnected quark terms (mP disc) somehow cancel the connected contribution (mP conn), all of which should vanish in the chiral limit. Actually the anomaly term alone and the sum of all contributions (total) almost coincide.

Fig. 4: The three-point correlation function $\Pi_3^G(x,y)$ of a quark, normalized to the free correlator and for the streamline configuration (IILM).

The final value of the quark spin expectation value from this calculation depends on the interactions of the instantons. Whereas random configurations of instantons and anti-instantons suggest that $g_A$ is indeed close to one, the interacting ensemble IILM shows a reduction of almost 50%. This is an clear indication that instanton effects might explain the proton spin puzzle.

REFERENCES