Constituent Quark Structure

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Abstract

In this talk I will motivate the the need for the constituent quark structure. I will also summarize results from the NJL model for the composites of the constituent quark and present an alternative QCD sum rule approach.

1. Introduction

The constituent quark was introduced over 30 years ago as a purely phenomenological entity to allow for a description of color singlet hadrons as bound states of smaller size objects, elements of the fundamental representation of color and flavour symmetry groups. The simple constituent quark model (CQM) Hamiltonians were written in the sixties and contained only the kinetic or mass term and short distance spin-spin interaction. Despite its simplicity a naive CQM Hamiltonian fits the spectrum of low lying baryon and meson multiplets to within 20% and leads to the universality of the constituent quark. Over the years more sophisticated phenomenological Hamiltonians have been proposed including a number of different confining interactions[1,2]. The quality of the original spectrum fit has been significantly reduced leaving still, however the bulk of the hadron mass coming from the constituent masses indicating that soft quarks are not too sensitive to the detailed behavior of the confining interaction at very large distances. It also indicates that at least for the ordinary (non exotic) hadrons there is no much room left for the constituent glue however a comprehensive study of the coupled channel problem with mixing to higher Fock sectors is still lacking. There are indications that the gluonic degrees of freedom may appear in a collective rather than single particle mode. In models such as the flux tube model, adiabatic approximation can be used to find the effective quark-quark interaction by averaging the quark-gluon Hamiltonian with respect to the gluonic configurations[3]. It is an open question which of the two, collective or constituent approach to the nonvalence degrees of freedom is more realistic. Another of the early successes of CQM was the ability to describe the magnetic moments of the ground state baryons. With the magnetic moments of the constituent quarks fixed at their canonical values, $\mu_q = e_q/2m_q$, CQM predictions for the baryon octet magnetic moments agree remarkably well with the experimental numbers.

Of course such naive valence, constituent picture cannot be right in particular when one attempts to build a unified model that would account for both low and high energy phenomena. In inelastic scattering at relatively low magnitude of the 4-momentum transfer, as the lab frame energy transfer, ν, increases contributions from nucleon resonances quickly dies out and at $x = Q^2/(2m_p\nu) \sim 1/3$ the cross section developes a broad structure which is associated with scattering off a constituent quark. As momentum resolution increases the the constituent quark dissolves and scattering off an infinite number of partonic layers start to dominate the large energy transfer region[4]. There are also reasons within the naive CQM itself to introduce the constituent quark structure. Since the π-ρ mass splitting is large the spin-spin interaction cannot be treated perturbatively. However the potential obtained through a nonrelativistic reduction of the one gluon exchange kernel is too singular and to make it a legal operator the Schrodinger equation, smearing, possibly associated with the constituent quark size is necessary. A good fit to the meson spectrum was obtained with the following Hamiltonian[1]

$$H = K + V_L + \langle V_S \rangle + \langle V_A \rangle, \tag{1}$$

with the consecutive terms standing for kinetic energy, linear long distance confining, short distance one gluon exchange and $q\bar{q}$ annihilation potentials respectively and brackets representing smearing with the quark form factor taken to be of Yukawa form. The size of the momentum space pion wave function in the harmonic oscillator approximation turns out to be of the order of $\beta \sim 360$ MeV thus leading to the core charge radius $\langle r^2 \rangle_{core} = 1/\beta^2 \sim 0.3\text{fm}^2$ only about 70% of the measured pion radius. The remaining 30% has to come from the constituent quark form factor yielding $\langle r^2 \rangle_q \sim 0.14\text{fm}^2$. As already mentioned, the need for the constituent quark structure emerges also as one tries to develop a model capable of providing a consistent low end high energy phenomenology. It can be shown that in order for the soft form factor, as discussed above, to smoothly connect to the inverse power low asymptotic behavior the constituent quark mass has to be taken as a dynamical quantity which decrease with the momentum transfers[5] Q^2 at least as $(1/Q^2)^\gamma$ with $\gamma > 1$. Similarly, a correct description of the hadron deep inelastic structure functions requires the constituent quark structure functions representing splitting of the constituent quark into valence and see partons. A good description of DIS data can be achieved in a constituent quark model with the splitting functions introduced by Altarelli[6] on the basis of the duality and Regge phenomenology with a universal set of parameters fitting both the nucleon[7] and pion[8] structure functions.

In the following section I will summarize results of the study of the constituent quark structure in the phenomenological approach based on the NJL Lagrangian. Section III is dedicated to illustrate a possibility for a more fundamental approach based on the study of the dynamics of the light degrees of freedom the presence of a static chromoelectric source.

2. Constituent quark structure in the NJL model[9]

In the NJL model quark dynamics is determined by a local four fermion interaction and as in many other similar approaches massless quarks acquire dynamically generated masses provided the strength of the effective interaction exceeds some critical value. With the interaction term

$$\mathcal{L}_{int} = G[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\psi)^2] \tag{2}$$

the critical coupling is $g^2_{crit} = 4\pi^2/3$ ($g^2 = G\Lambda^2$ where Λ is the euclidean cutoff), and for $g^2/g^2_{crit} \sim 1.3$ the dynamical quark mass is $m_q \sim 330\text{MeV}$. Gauging the original Lagrangian the quark-photon vertex form factor, F is determined by the dynamical quark propagator and the $q\bar{q}$ scattering amplitude given by $\mathcal{L}_{int}$. The singularity structure of F is identical to that of the full $q\bar{q}$ scattering amplitude, T which in turn determines the meson spectrum. Thus in the NJL the electromagnetic quark form factor become dominated by the low lying vector mesons and similarly higher mass mesons determine the behavior of form factors in other channels. Solving for F leads to the electric charge radius of the constituent quark $\langle r^2 \rangle_q \sim 0.11\text{fm}^2$ in agreement with the quark model requirements. It also leads to a negligible anomalous constituent quark magnetic moment in agreement with the predictions of the core CQM. Due to the $\pi - a_1$ mixing the strength of the axial constituent quark coupling $(g_A)_q$ is renormalized. The NJL model predicts $(g_A/g_V)_q \sim 3/4$ which combined with the core CQM prediction $(G_A/G_V)_N = 5/3$ for the nucleon axial charge gives $(G_A/G_V)_N = 5/4$ in agreement with the data.

3. Constituent quark structure and the heavy mesons

If a light quark is placed in a static chromoelectric field which polarizes the vacuum it effectively becomes a dressed constituent quark. In practice the static chromoelectric source is hard to realize. However a single heavy quark with mass, m_Q much larger than the QCD scale, Λ_{QCD} can be considered as such because corrections the static approximation are of the order of m_Q/Λ_{QCD}. This is a simple model of the heavy meson. The important consequence of the presence of the heavy quark is that to leading order in $1/m_Q$ heavy and light degrees of freedom decouple and the structure of the heavy meson becomes solely determined by the dynamics of the light constituents as can be shown by taking the $m_Q \to \infty$ limit in heavy quark sector of the QCD Lagrangian. In the effective theory obtained in such a way the heavy quark interactions are spin independent and lead to a separate conservation of the heavy quark spin and total angular momentum of the light degrees of freedom[10]. Experimentally this prediction is well confirmed. The D^*, D mass splitting is about 150MeV while the of B^*,B is only about 50MeV in agreement with the pattern of the $1/m_Q$ corrections. The light mock in the heavy meson caries the flavor and color quantum numbers of the valence light quark and due to the spin decoupling it also has a well define total angular momentum. For the spin-0 meson the light cloud is in the $J = 1/2$ state and thus may be identified with the ground state of the constituent quark. Due to an explicit flavour heavy mesons decay weakly through the heavy flavour transition and/or annihilation and it is possible to isolate decay modes such that in a decay process of the heavy quark the state of the light spectators remains unchanged to the leading order in $1/m_Q$. Measurement of such decay modes may provide important information on the nonperturbative behavior of the light degrees of freedom in the presence of a chromoelectric source and on the constituent quark structure. In particular it can be shown that the hadronic part of the semileptonic decay, $B \to Dl\nu_{\bar{l}}$, in the $m_b, m_c \to \infty$ is determined by a single, universal function $\xi(w)$ of the velocity transfer, $w = 1 - Q^2/2m_Q^2$, called the Isgur-Wise form factor. The universal function in turn is fully determined by the wave function of the light degrees of freedom despite the fact that it is defined through a matrix element of an operator with heavy quarks only[11]. QCD sum rule methods have been used to relate $\xi(w)$ to the properties of the constituent quark. In Ref. [12] a QCD sum rule analysis of the vacuum three-point correlator was used to constrain the euclidean light quark correlator $S(z) = \langle 0|\bar{q}(z)q(0)|0\rangle$. Numerical analysis of the sum rule gives the constituent quark mass to be $m_q \sim 360$MeV in good agreement with CQM. A different sum rule was developed in Ref. [13] and used to relate ξ to the matrix element, $\phi(E)$ which measures energy distribution of the light quark in the heavy meson

$$\phi(E) = -i \int dt e^{iEt} \langle 0|\bar{q}(t) \frac{\not{P}}{m_Q^2} \gamma_5 Q(0)|P\rangle. \tag{3}$$

To leading order in $1/m_Q$, $\phi(E)$ also represents the distribution of the QCD quark energies in the light constituent quark. With the normalization of ϕ fixed by the condition $\int dE\phi(E) = f_h$ with f_h being the heavy meson decay constant the sum rule determines large energy behaviour $E \sim E_c$ ($E_c \sim 2E_0$ is the continuum threshold energy) of $\phi(E)$

$$\phi(E) \sim \frac{f_h}{E_c}(2 + O((1 - \frac{E}{E_c})^2). \tag{4}$$

A pure $\bar{Q}q$ heavy meson of definite energy E_0 requires the light quark also to have a definite energy and if $\bar{Q}$ and q interact through a static chromoelectric potential the distribution amplitude should be given by

$$\phi(E) = f_h \delta(E - E_0). \tag{5}$$

Eq. (**??**) indicates however the existence of large contributions to $\phi(E)$ coming from energies other then E_0. It can be estimated that as much as 50% of the normalization of ϕ can attributed to $E > E_0$ region. This result implies large gluon and/or sea quark amplitudes in heavy quark systems or in other words a nontrivial structure of the constituent quark.

Finally I will shortly discuss the QCD evolution of the quark energy distribution amplitude. The matrix element in Eq.(**??**) is normalized at $\mu \sim E_0 \sim 300 - 500$MeV. As μ increases the dressed light quark evolves in the direction of the bare, current quark and the perturbative structure of the constituent quark is revealed. The QCD evolution equation for the moments $M_n = \int dE E^n \phi(E)$ can be set up in the effective theory and the one loop calculation has recently been completed[14]. In particular it can be shown that in the limit $\mu \to \infty$ the asymptotic distribution amplitude approaches the static one given by Eq. (**??**)

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