Pion loop fluctuations of constituent quarks and baryons

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The implications of the pion (meson) degrees of freedom for baryon properties, taken at the constituent quark and baryon levels are compared. It is shown that there is a dramatic qualitative difference between two approaches.

The role of pion degrees of freedom for baryon observables was appreciated in the strong coupling theories of the 1950's and later formed the basis of the Skyrme model and the chiral bag models. Consideration of the pion loop fluctuations on the baryon level, either within the traditional strong coupling approach or within modern ChPT for baryons reveals several problems:

(i) The $g_{\pi NN}^2/4\pi \sim 14$, which indicates that the loop expansion diverges. The expansion within BChPT indicates a lack of convergence as well;
(ii) The full set of intermediate baryon resonances has to be taken into account in the calculation, which consequently involves a large number of parameters;
(iii) No information about the underlying quark structure is built into the loop integrals;
(iv) $m_N \sim \Lambda_X$.

In the region of spontaneously broken chiral symmetry, where the pion degrees of freedom are important, the structure of the elementary excitations of the QCD vacuum can be approximately reproduced by absorption of the scalar interaction between bare (current) quarks in the QCD vacuum (which is responsible for the chiral symmetry breaking) into the mass of the quasiparticles, i.e. the constituent quarks. Thus in the low-energy regime the proper chiral dynamics is due to the pion-constituent quark coupling. In this case:

(i) The $\pi QQ$ coupling constant is relatively small, $g_{\pi QQ}^2/4\pi \sim 0.6 - 0.7$;
(ii) All possible intermediate baryon resonances are taken into account automatically by considering the $u$ and $d$ quarks in the loop amplitudes;
(iii) The role of the underlying $SU(6)$ quark structure is revealed in relations between different observables;
(iv) $(m_Q/\Lambda_X)^2 \sim 0.1$.

An example of the conceptual difference between the treatment of the mesonic fluctuations of constituent quarks, on the one hand, and (directly) of baryons, on the other hand, is in order. In the latter the mesonic loops imply an infinite shift of the baryon mass in
the chiral limit, which is balanced by the phenomenologically determined counter-terms. Consideration of the mesonic degrees of freedom in such approaches yields information on the corrections from the finite masses of current quarks, but not on the origin of the nucleon mass nor on the octet-decuplet splitting in the chiral limit. In the chiral constituent quark model the role of the meson degrees of freedom is broader. On the one hand meson fluctuations contribute to the self-energy of the constituent quarks (loops at the quark level), but on the other hand they imply a strong flavor-dependent interaction between the constituent quarks (meson exchange interaction between different quarks), which yields an octet-decuplet splitting in the chiral limit [1].

The pion-exchange interaction contains both the ultraviolet (short-range) part, which is independent of the pion mass, and the infrared (Yukawa) part. The latter one is important for the long-range nuclear force, but it does not produce any significant effect in the baryon because of its small matter radius. The short-range part of the pion-exchange interaction produces a flavor-spin dependent force between quarks and has a range \( \Lambda^{-1} \). While the infrared (Yukawa) part of the interaction vanishes in the chiral limit, the ultraviolet part does not. This means that in some sense the short-range part of the pion-exchange interaction is "more fundamental" than its Yukawa part. Note that this short-range interaction stems from the \( \gamma_5 \) structure of the pion-quark vertex (i.e. exclusively from the quantum numbers of the pion) and hence is demanded by the Lorentz invariance. This short-range part of the interaction, combined with the \( SU(6) \) structure of the zero order baryon wave functions (which is demanded by the large \( N_c \) limit in QCD), provides a basis for the explanation of the low-lying baryon spectrum [2]. It should be noted that this short-range interaction cannot be obtained by considering the pion loops at the baryon level with the ground \( N \) and \( \Delta \) states as the intermediate states within the loop [3]. At the baryon level one needs to consider the whole infinite tower of the radially excited states within the loop in order to meet this short-range meson exchange interaction. This implies that the meson-baryon or quark models which employ only the subspace of the \( \pi N \) and \( \pi \Delta \) states are very incomplete and therefore do not take into account the most important short-range effects of the pion (meson) degrees of freedom for baryon structure.

As another example consider the different role of the pion cloud for magnetic moments in both approaches. In hadronic models the pion loops is the only source for the nucleon anomalous magnetic moment. In contrast, within the naive quark model the nucleon magnetic moments are exclusively due to the intrinsic \( SU(6) \) quark structure of the baryon. The small pion-quark coupling constant together with the additional small parameter \( (m_Q/\Lambda_\chi)^2 \sim 0.1 \) guarantee that the loop corrections to the naive quark model predictions (i.e. loops at the constituent quark level) are not large [4]. For the absolute values of the proton and neutron anomalous magnetic moments one finds contributions at the level of 5-10%. What is more important, the ratio \( \mu_n/\mu_p \), comes out to be only 2% above the empirical ratio 0.68, while the naive quark model prediction, 2/3, is 2% below.

The pion loop corrections supply only a tiny contribution to the neutron Dirac charge radius [4]. They therefore do not perturb the satisfactory description of the negative mean square radius of the neutron, which is implied by the empirical value of the neutron magnetic moment (Foldy term).

The kaon loop fluctuations of the valence \( u \) and \( d \) constituent quarks induce only a very
small strangeness magnetic moment of the proton [5], which is in the range -0.01 – -0.05, and is well consistent with the most recent data from the SAMPLE experiment, reported at this conference. This is again in contrast with the large negative strange magnetic moment that is implied by the kaon loop fluctuations considered at the baryon level.

REFERENCES