



Effective Lagrangian approach to multi-quark interactions*

A. A. Osipov, B. Hiller, A. H. Blin

Centro de Física Computacional, Departamento de Física da Universidade de Coimbra,
3004-516 Coimbra, Portugal

Abstract. In this workshop we have presented the results obtained in the three-flavour ($N_f = 3$) Nambu–Jona-Lasinio model Lagrangian which includes all non-derivative vertices at NLO in the $1/N_c$ expansion of spin zero multi-quark interactions. In particular the role played by the explicit chiral symmetry breaking interactions has been discussed in comparison with previous model Lagrangians.

The subject of this year’s Bled workshop is “Quark masses and hadron spectra”. The understanding of the origin of masses from fundamental principles may have moved a step closer with the announcement of the existence of the Higgs, however the reason for the hierarchy of masses observed for several families of leptons and quarks still eludes us. The current quark masses are external to the gauge principle underlying the foundations of QCD. In an effective approach to QCD the most innocuous way is to consider them born from external sources interacting with originally massless fields which comply with all the symmetries. If in addition the study of strong interactions is limited to the energy range which is of order $\Lambda \simeq 4\pi f_\pi \sim 1 \text{ GeV}$ [1], where Λ characterizes the scale for spontaneous chiral symmetry χ_S breaking, a firm set-up for its systematic inclusion is supplied by the seminal papers of Nambu and Jona-Lasinio (NJL) [2].

Our procedure relies on the very general assumption that this scale determines the hierarchy of local multi-quark interactions which model QCD at low energies. It has been pointed out in [3,4] that it is sufficient to truncate the tower of multi-quark interactions at 8 quarks (q) to complete in 4D the number of vertices relevant at the scale of dynamical chiral symmetry breaking.

The $U(1)_A$ symmetry breaking ’t Hooft ($2N_f$) flavor determinant [5,6] adds $1/N_c$ suppressed interactions to the original NJL Lagrangian [7,8]. Having first focussed on the resolution of the instability of this model’s effective potential [9], we have enlarged the Lagrangian by a general set of equally suppressed spin zero $8q$ interactions [10,11].

Later on, showing that the N_c counting rules are congruent with the classification of vertices in terms of the χ_S breaking scale, we have taken into consideration the terms of higher order in the current quark-mass expansion [12,13],

* Talk delivered by B. Hiller

which are responsible for the explicit chiral symmetry breaking at the same order as the 't Hooft determinant and eight quark terms previously analyzed. The standard mass term of the free Lagrangian is only a part of the more complicated picture arising in effective models beyond leading order [14]. Chiral perturbation theory [15–17] gives a well-known example of a self consistent accounting of the mass terms, order by order, in an expansion in the masses themselves.

Using path integral bosonization techniques which take appropriately into account the quark mass differences [18, 19], the mesonic Lagrangian up to three-point mesonic vertices is obtained in [13].

We end up with $4 + 10 = 14$ low-energy constants at leading and NLO of the effective $1/N_c$ expansion. The model parameters are fully controlled on the theoretical side by symmetry arguments and on the experimental side by the characteristics of the low lying pseudoscalars and scalars. The number of observables described until now by far surpasses the number of parameters [13].

The tree level bosonized Lagrangian carries either signatures of violation of the Zweig-rule or of admixtures of $q^2\bar{q}^2$ to the quark-antiquark states. Elsewhere these are obtained by considering explicitly meson loop corrections, tetraquark configurations and so on [20–31].

By calculating the mass spectra and the strong decays of the scalars, one can realize which multi-quark interactions are most relevant at the scale of spontaneous χ_S breaking. On the other hand, by analyzing the two photon radiative decays, where a different scale, associated with the electromagnetic interaction, comes into play, one can study the possible recombinations of quarks inside the hadron.

Our main results are so far:

1. We achieve total agreement with the empirical low lying pseudoscalar meson spectrum. The current quark mass dependent interaction terms mainly responsible for the fit belong to the class of OZI-violating interactions, representing additional corrections to the 't Hooft $U_A(1)$ breaking mechanism. Explicit χ_S breaking effects in interactions are essential to obtain the empirical ordering $m_\kappa < m_\eta$ and the magnitude of the splitting. The fit of the $\eta-\eta'$ mass splitting together with the overall successful description of the whole set of low-energy pseudoscalar characteristics is actually a solution for a long standing problem of NJL-type models.
2. We are also capable to describe the spectrum of the light scalar nonet. The explicit χ_S breaking terms related with $q^2\bar{q}^2$ admixtures are the main source of the fit associated with the empirical ordering $m_{\kappa_0} < m_{a_0} \sim m_{f_0}$. On the other hand, the mixing angle of the singlet-octet scalar states θ_S as well as the mass of the σ meson are strongly affected by OZI-violating short range forces.
3. With all parameters of the model fixed by the spectra we analyzed a bulk of two body decays at tree level of the bosonic Lagrangian: the strong decays of the scalars $\sigma \rightarrow \pi\pi$, $f_0(980) \rightarrow \pi\pi$, $\kappa(800) \rightarrow \pi K$, $a_0(980) \rightarrow \pi\eta$, as well as the two photon decays of $a_0(980)$, $f_0(980)$ and σ mesons and the anomalous decays of the pseudoscalars $\pi \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$ and $\eta' \rightarrow \gamma\gamma$.

Our results for the strong decays of the scalars are within the current expectations. The radiative decays of the scalars are smaller than the observed values for the $f_0(980)$ and the σ , but reasonable for the a_0 .

We obtain that the $a_0(980)$ meson couples with a large strength of the multi-quark components to the two kaon channel in its strong decay to two pions, but evidences a dominant $q\bar{q}$ component in its radiative decay. As opposed to this, the σ and $f_0(980)$ mesons do not display an enhanced $q\bar{q}$ component neither in their two photon decays nor in the strong decays. The widths of the $a_0(980) \rightarrow \pi\eta$ and $f_0(980) \rightarrow \pi\pi$ decays are well accommodated within a Flatté description. We corroborate other model calculations in which the coupling of the $f_0(980)$ and $a_0(980)$ mesons to the $K\bar{K}$ channel is needed for the description of the decays $f_0(980) \rightarrow \pi\pi$ and $a_0(980) \rightarrow \pi\eta$. We find that this coupling is most crucial for the latter process.

The radiative decays of the scalar mesons into two photons show that the main channel for the $a_0(980)$ decay proceeds through coupling to a $q\bar{q}$ state, while the radiative decays of singlet-octet states σ, f_0 must proceed through more complex structures. This does not mean that the a_0 meson is mainly a $q\bar{q}$ state, but that the multi-quark component with the large strength in the two kaon channel, important for the reduction of the $a_0\pi\eta$ strong decay width, is not the leading process in the two photon decay of this meson.

Finally, the radiative decays of the pseudoscalars are in very good agreement with data.

4. The response to the external parameters T, μ has been recently addressed in [32], with implications on strange quark matter formation. In the early version of the model Lagrangian without the explicit NLO χ_S breaking terms one obtains that although the vacuum properties remain almost insensitive to the $8q$ interactions, their effects are remarkable for medium and thermal properties [33–38], as well as in presence of a strong constant magnetic field [39–42].

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Povzetki v slovenščini

Tetrakvarki v limiti kromodinamike z velikim številom barv

Thomas Cohen

Department of Physics, University of Maryland, College Park, MD 20742-4111

Iskanje tetrakvarkov v normalnih in v eksotičnih spektrih še vedno ni prepričljivo, niti eksperimentalno niti teoretično. Podpora pa narašča. Odprto vprašanje je, ali lahko vezani tetrakvarki obstajajo v limiti velikega števila barv. Obstajajo pa na primer v zanimivi antisimetrični varianti kromodinamike.

Sestavljeni šibki bozoni na Velikem hadronskem trkalniku

Harald Fritzsch

Department für Physik, Ludwig-Maximilians-Universität München, Germany

V sestavljenem modelu šibkih bozonov proučujemo vzbujene bozone, zlasti tiste v stanju p . Stanje z najmanjšo maso poistovetimo z bozonom, ki so ga nedavno odkrili na Velikem hadronskem trkalniku v CERNu. Proučujemo značilne lastnosti vzbujenih šibkih bozonov, zlasti njihove razpade v šibke bozone in fotone.

Vpeljava večkvarkovskih interakcij z efektivno Lagrangeovo gostoto

A. A. Osipov, B. Hiller, A. H. Blin

Centro de Física Computacional, Departamento de Física da Universidade de Coimbra, 3004-516 Coimbra, Portugal

Predstavili smo rezultate razširjenega modela Nambuja in Jona-Lasinia s tremi okusi kvarkov. V Lagrangeovo gostoto smo vključili vsa vozlišča brez odvodov, v naslednjem redu razvoja po recipročnem številu barv, za večkvarkovske interakcije s spinom nič. Prikazali smo zlasti vlogo interakcij, ki eksplicitno zlomijo kiralno simetrijo, in njihov učinek primerjali s prejšnjimi modeli.