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Heavy hadron spectroscopy: A quark model perspective

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Abstract

We present recent results of hadron spectroscopy and hadron–hadron interaction from the perspective of constituent quark models. We pay special attention to the role played by higher order Fock space components in the hadron spectra and the connection of this extension with the hadron–hadron interaction. The main goal of our description is to obtain a coherent understanding of the low-energy hadron phenomenology without enforcing any particular model, to constrain its characteristics and learn about low-energy realization of the theory.

Keywords: Heavy hadrons; Constituent quark model; Many-quark systems

1. Introduction

For almost thirty years after the discovery of the J/ψ and its excitations, the so-called November revolution [1], heavy hadron spectroscopy was at rest. Paraphrasing Lord Kelvin famous speech [2], by 2003 there were only two clouds on the horizon obscuring *the beauty and clearness of the dynamical theory*. In the hadron spectra these *two clouds* were on the one hand the missing resonance problem, i.e., all quark models predict a proliferation of excited states which have not been measured, and, on the other hand, the observation by BaBar of an open-charm meson, the $D^*_{sJ}(2317)$, whose properties were quite different from those predicted by quark potential models.

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Since those peaceful days an increase on both amount and quality of experimental data has shown quite a different picture, far more involved and convoluted, with the observation of the well-known $X(3872)$, the $X(3940)$, $Y(3940)$, $Z(3930)$, $Y(4140)$, and several other states. Based on Gell-Mann conjecture [3] the hadronic experimental data were classified either as $q\bar{q}$ or qqq states according to SU(3) irreducible representations, nowadays this hypothesis may be in question. Therefore, the study of the role played by higher order Fock space components in the hadron spectra, allowed by the Gell-Mann classification, is an interesting issue to address.

In this talk we give an overview of a project for getting a coherent understanding of the low-energy hadron phenomenology from the perspective of constituent quark models [4]. We will make emphasis on three different aspects. Firstly, we will address the study of meson spectroscopy in an enlarged Hilbert space considering many-quark components. This seems nowadays unavoidable to understand the experimental data and it builds a bridge towards the description in terms of hadronic degrees of freedom. Secondly, the same scheme used to describe the hadron spectroscopy should be valid for describing the low-energy meson–meson scattering. In other words, contributions to the hadron spectroscopy arising from many-quark components allowed in the Gell-Mann scheme, should also be recovered by means of hadron–hadron scattering using a full set of states. Finally, we will review our recent efforts to describe the structure of heavy baryons containing charm or bottom quarks.

2. Meson spectroscopy beyond the naive quark-model

Many-quark systems present a richer, and therefore more complicated, color structure than standard hadrons built with a quark–antiquark pair or three quarks. While the color wave function for ordinary mesons and baryons leads to a single vector, in the case of four-quark states there are different vectors driving to a singlet color state out of either colorless or colored quark–antiquark two-body components. Thus, when dealing with four-quark states a basic important question is whether we are in front of a single colorless meson–meson molecule or a compact state, defined as a system with two-body colored components. Whereas the first structure would be natural in the naive quark model, the second one would open a new area in hadron spectroscopy.

Let us start by defining a *physical channel* as a four-quark state made of two quark–antiquark color singlets. In Ref. [5] the formalism to evaluate the probability of the different physical channels for an arbitrary four-quark wave function was derived. For this purpose any hidden-color vector of a four-quark color basis, i.e., vectors with non-singlet internal color couplings, was expanded in terms of singlet–singlet color vectors. Such a procedure gives rise to a wave function expanded in terms of nonorthogonal vectors belonging to different orthogonal basis, and therefore the determination of the probability of physical channels becomes cumbersome. Such nonorthogonal expansions are common in other fields of science, like chemical physics [6], however they have not been properly discussed until now in the context of the multiquark phenomenology, i.e., *color chemistry*. We have derived the two hermitian operators that are well-defined projectors on the physical singlet–singlet color states $|11\rangle_c$ and $|1'1'\rangle_c$. Using these operators the probabilities for finding singlet–singlet color components for an arbitrary four-quark state $|\Psi\rangle$ are given by,

$$
\begin{aligned}
P^{|\Psi\rangle}\big([11]\big) &= \frac{1}{2(1-|_c\langle 11|1'1'\rangle_c|^2)}\big[\langle\Psi|P\hat{Q}|\Psi\rangle + \langle\Psi|\hat{Q}P|\Psi\rangle\big],\\
P^{|\Psi\rangle}\big([1'1']\big) &= \frac{1}{2(1-|_c\langle 11|1'1'\rangle_c|^2)}\big[\langle\Psi|\hat{P}Q|\Psi\rangle + \langle\Psi|Q\hat{P}|\Psi\rangle\big],
\end{aligned}
\tag{1}
$$