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Few-Body Systems

Multiquark States in a Goldstone Boson Exchange Model

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Abstract. We discuss the stability of multiquark systems containing heavy flavours. We show that the Goldstone boson exchange model gives results at variance with one-gluon-exchange models.

1 Introduction

The study of exotic hadrons formed of more than three quarks and/or antiquarks ($q^m\overline{q}^n$ with $m+n>3$) is a natural development of QCD inspired models. Both theoretical and experimental interest has been raised so far by particles described by the colour state $[222]_C$. These are the tetraquarks $q^2\overline{q}^2$ [1], the pentaquarks $q^4\overline{q}$ [2, 3] and the hexaquarks q^6 [1]. From theoretical general arguments [4, 5], one expects an increase in stability of multiquark systems if they contain heavy flavours $Q = c$ or b.

In the heavy sector, experiments are being planned at CERN and Fermilab to search for new heavy hadrons and in particular for doubly charmed tetraquarks [6]. Recently , the first search for pentaquarks with the flavour content $uuds\overline{c}$ and $udds\overline{c}$ has just been reported [7]. Within the confidence level of the analyzed experiments, no convincing evidence for the production of the above strange pentaquarks has been observed so far.

The theoretical predictions are model dependent. Here we are concerned with constituent quark models which simulate the low-energy limit of QCD. We compare results from models where the spin-dependent term of the quark-quark interaction is described by the chromomagnetic part of the one gluon exchange (OGE) interaction [8] with results we obtained from the Goldstone boson exchange (GBE) model [9, 10, 11, 12]. In this model the hyperfine splitting in hadrons is due to the short-range part of the Goldstone boson exchange interaction between quarks, instead of the OGE interaction of conventional

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models. The GBE interaction is flavour-dependent and its main merit is that it reproduces the correct ordering of positive and negative parity states in all parts of the considered spectrum. Moreover, the GBE interaction induces a strong short-range repulsion in the Λ-Λ system, which suggests that a deeply bound H-baryon should not exist [13]. This is in agreement with the high-sensitivity experiments at Brookhaven [14] where no evidence for H production has been found.

In the stability problem we are interested in the quantity

$$\Delta E = E(q^m \overline{q}^n) - E_T \tag{1}$$

where $E(q^m \overline{q}^n)$ represents the multiquark energy and E_T is the lowest threshold energy for dissociation into two hadrons: two mesons for tetraquarks, a baryon + a meson for pentaquarks and two baryons for hexaquarks. A negative ΔE suggests the possibility of a stable compact mutiquark system.

According to Ref. [9] there is no meson exchange interaction between quarks and antiquarks. It is assumed that the $q\overline{q}$ pseudoscalar pairs are automatically included in the GBE interaction. Therefore the light quark and the heavy antiquark interact via the confinement potential only and the model Hamiltonian contains GBE interactions only between light quarks.

2 The Hamiltonian

The GBE Hamiltonian considered below has the form [10] :

$$H = \sum_i m_i + \sum_i \frac{\boldsymbol{p}_i^2}{2m_i} - \frac{(\sum_i \boldsymbol{p}_i)^2}{2\sum_i m_i} + \sum_{i<j} V_{\text{conf}}(r_{ij}) + \sum_{i<j} V_\chi(r_{ij}) \,, \tag{2}$$

with the linear confining interaction :

$$V_{\text{conf}}(r_{ij}) = -\frac{3}{8}\lambda_i^c \cdot \lambda_j^c \, C \, r_{ij} \,, \tag{3}$$

and the spin–spin component of the GBE interaction in its $SU_F(3)$ form :

$$\begin{aligned} V_\chi(r_{ij}) &= \left\{ \sum_{F=1}^{3} V_\pi(r_{ij}) \lambda_i^F \lambda_j^F \right. \\ &+ \left. \sum_{F=4}^{7} V_K(r_{ij}) \lambda_i^F \lambda_j^F + V_\eta(r_{ij}) \lambda_i^8 \lambda_j^8 + V_{\eta'}(r_{ij}) \lambda_i^0 \lambda_j^0 \right\} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, \end{aligned} \tag{4}$$

with $\lambda^0 = \sqrt{2/3}\,\mathbf{1}$, where $\mathbf{1}$ is the 3×3 unit matrix. The interaction (2) contains $\gamma = \pi, K, \eta$ and η' meson-exchange terms and the form of $V_\gamma\,(r_{ij})$ is given as the sum of two distinct contributions : a Yukawa-type potential containing the mass of the exchanged meson and a short-range contribution of opposite sign, the role of which is crucial in baryon spectroscopy. For a given meson γ, the

Table 3.1. Results for ΔE , Eq.(1), for charmed exotic hadrons

System	OGE	GBE
$u\ u\ \bar{c}\ \bar{c}$	19 MeV [15]	-185 MeV [16]
$u\ u\ d\ d\ \bar{c}\ (P=+1)$	unbound	-76 MeV [17]
$u\ u\ d\ s\ \bar{c}\ (P=-1)$	-51 MeV [18]	488 Mev [19]
$u\ u\ d\ d\ s\ c$	-7.7 MeV [20]	625 MeV [21]

exchange potential is

$$V_\gamma(r) = \frac{g_\gamma^2}{4\pi} \frac{1}{12 m_i m_j} \{\theta(r-r_0)\mu_\gamma^2 \frac{e^{-\mu_\gamma r}}{r} - \frac{4}{\sqrt{\pi}}\alpha^3 \exp(-\alpha^2(r-r_0)^2)\} \tag{5}$$

For the Hamiltonian (2)-(5), we use the parameters of Refs.[10, 13]. These are :

$$\begin{aligned} \tfrac{g_{\pi q}^2}{4\pi} = \tfrac{g_{\eta q}^2}{4\pi} = \tfrac{g_{Kq}^2}{4\pi} = 0.67,\ \tfrac{g_{\eta' q}^2}{4\pi} = 1.206, \\ r_0 = 0.43\, fm,\ \alpha = 2.91\, fm^{-1},\ \ C = 0.474\, fm^{-2}, \\ m_{u,d} = 340\, MeV,\ m_s = 440\, MeV, \\ \mu_\pi = 139\, MeV,\ \mu_\eta = 547\, MeV,\ \mu_{\eta'} = 958\, MeV,\ \mu_K = 495\, MeV. \end{aligned} \tag{6}$$

3 Results

Values of ΔE , Eq. (1), for charmed systems are presented in the table both for OGE and GBE models. Details of our calculations based on the GBE model can be found in refs. [16, 17, 19, 21] together with results for $Q = b$.

One can see that the OGE and the GBE interactions predict contradictory results for the charmed exotic systems presented here: while the GBE interaction stabilizes a given system, the OGE interaction destabilizes it and vice versa. The following remarks are in order:

- As the $u\ u\ d\ d\ \bar{c}\ (P=-1)$ pentaquarks are predicted to be unbound by a chromomagnetic interaction [18], the same system but with positive parity is expected to be even more unstable due to the increase in the kinetic energy produced by the excitation of a quark to the p-shell. While the OGE interaction favours negative parity pentaquarks with strangeness, the best candidates predicted by the GBE interaction have positive parity and are nonstrange [17].
- The GBE interaction destabilizes the hexaquarks in the presence of one or even two heavy quarks [21].

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