PENTAQUARKS
– SOME THEORETICAL ASPECTS –

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In this report, we briefly discuss some theoretical aspects of pentaquarks which are of great relevance to our present understanding of hadron physics. Emphasis is put on the role of chiral symmetry, as well as results from a recent five body calculations in a quark model.

1. Introduction

The observation of an exotic pentaquark baryon Θ^+ [1] predicted first by Diakonov et al [2] has given a great opportunity in hadron physics to reconsider the long-standing problem of the exotic hadrons [3,4]. Now, since many experimental results have reported no signal, the existence itself is questioned [5]. However, it is fare to say that the situation is not yet settled after the vast amount of theoretical and experimental efforts, which would be an indication that our understanding of hadron physics is not quite achieved. Therefore, it is important to test carefully if our present understanding of hadron physics is able to accommodate such states with expectedly *exotic* properties.

Among various theoretical methods we consider two approcaches; one is to incorporate chiral symmetry with spontaneous breaking, and the other is to deal with (constituent) quarks with some residual interactions. In the former description, the strong interaction of the pion may affect hadron properties in many respects. Since the pions are light, they can fluctuate around a hadron, contributing to multi-quark components in its wave function, which may cause some exotic properties of hadrons. The latter description is based on the empirical success of the quark models with

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inter-quark correlations. Here the question is whether such a simple (but considerably powerful so far) picture will persist in the new petaquark structure.

2. Pion quark interaction

In the first example we discuss the role of the pions for the fundamental properties such as the parity of the pentaquark. We use the chiral bag model [6], where the strength of the pion interaction can be controlled by the bag size; for small size the model reduces to the Skyrmion with strong pion filed, while for large size it reduces to the MIT bag model where the pion disappears [7]. In Fig. 1, energies of several low lying states are shown as functions of the chiral angle F at the bag surface, a measure of the strength of the pion interaction. The us quarks take the *hedgehog* states (labeled by h) as classified by the "grand" spin and parity, K^P, and their eigenenergies vary as F is varied. However, those of strange quarks do not change as they are not subject to the pion interaction (dashed line).

In Fig. 1 also shown is how five quarks $uudd\bar{s}$ occupy the levels for the pentaquark. Three ud quarks always occupy the lowest 0^+ state, and the $\bar{s}$ state stays in the constant 0^+ level. When the pion is weak, the second lowest level for the ud quarks is 1^+ where the fourth quark enters. This configuration has negative parity, since the $\bar{s}$ quark carries intrinsic negative parity. This corresponds to the one of the naive quark model. Now, as the pion strength is increased, the 1^- state becomes lower than the 1^+ state, where the fourth quark enters. Hence the parity of the pentaquark becomes positive at and beyond this pion strength. This corresponds to the result of the chiral soliton and the Skyrme model.

In the quark model, the positive parity pentaquark requires one occupation in the $l = 1$ state which naively costs an extra energy. The pion interaction, however, lowers the $l = 1$ state than one of the $l = 0$ states (corresponding to the 1^+ state in Fig. 1) [8]. Therefore, it is very interesting to determine the parity of Θ^+ once its existence is established.

3. Full calculation for five quark states

The second example shows the role of quark interactions in a conventional quark model. Our purpose here is to investigate whether diquarks are developed in the pentaquark as it was emphasized in the literature [9]. Such a configuration affects significantly the properties of the pentaquarks including parity. We have performed in Ref. [10] the full five-body calculation

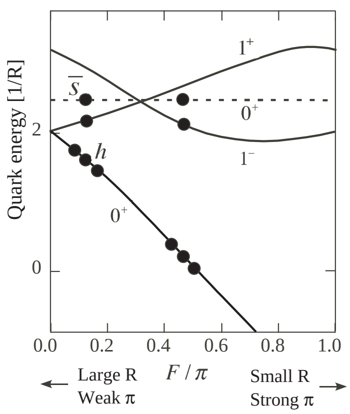

Figure 1. Quark energies in the chiral bag as functions of the chiral angle (pion strength) at the bag surface.

for Θ^+ as KN *resonance* states. The $qqqq\bar{q}$ (pseudo) bound states are first solved very accurately which are then coupled by the scattering states of the clusters of qqq and $\bar{q}q$.

Since this is the first attempt of such high accuracy coupled channel calculation, we have chosen one of the standard quark model hamiltonians containing of a confining potential of a harmonic oscillator and the color-magnetic interaction. This hamiltonian among others accommodates a large attraction in the scalar-isoscalar diquark channel. At the same time, however, it yields twice as strong attraction in the $q\bar{q}$ channel. This is known for some time, and may become important in exotic states which contain $\bar{q}$.

We have solved the five body system for the two cases of $J^P = 1/2^{\pm}$, and found the followings [10]:

(1) For the $1/2^+$ state, we found a resonance at ~ 500 MeV above the KN threshold with a width ~ 100 MeV. This configuration includes one $l = 1$ excitation of the quark model $\sim (0s)^4 1p$. The wave function indicates some correlation in qq channels, but we found stronger correlation in the $\bar{s}q$ channel.

(2) For the $1/2^-$ state, we found a resonance again at ~ 500 MeV above the KN threshold but with a very narrow width $\sim$ few MeV. The state does not corresponds to the naively expected ground state of $(0s)^5$ configuration. The latter is simply the KN scattering state and can not be a narrow resonance. The resonance wave function is complicated as expressed as a superposition of many states of basis functions we employed.

From this study, we have seen that the naive expectation from a model Hamiltonian might not necessarily be realized in pentaquark structure.

In multi-quark configurations, competing interactions between qq and $\bar{q}q$ which does not appear in the conventional states must be treated carefully.

4. Final remarks

We have discussed the role of pions and quark interactions for the exotic pentaquarks in two effective approaches of QCD. In principle, they have the common origin, but with different aspects of QCD. In both examples, either the pionic or diquark correlations strongly affects the basic properties of Θ^+ such as parity. This contrasts with our knowledge of the conventional hadrons. The main reason for this is that in exotic multi-quark channels, the configurations are always decomposed into a sum of color singlet states of minimal number of quarks (three for baryons and two for mesons). Hence the existence of (quasi) stable exotic hadrons depends crucially on the nature of colored interactions inside multi-quark configurations. Such study is not yet completed and should be an important subject in hadron physics.

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References

1. T. Nakano *et al.* [LEPS Collaboration], Phys. Rev. Lett. **91**, 012002 (2003).
2. D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. **A359**, 305 (1997).
3. For recent activities, see for instance, the proceedings of the international workshop PENTAQUARK04, held at SPring-8, Japan, July (2004); edited by A. Hosaka and T. Hotta, World Scientific (2005).
4. For researches before the recent activities, see, for instance, H. Lipkin, Nucl. Phys. A625 (1997) 207-219.
5. For a recent review, see for instance, K. Hicks, arXiv:hep-ex/0504027.
6. A. Hosaka, Phys. Lett. B **571**, 55 (2003).
7. A. Hosaka and H. Toki, Phys. Rept. **277**, 65 (1996).
8. Fl. Stancu, D.O. Riska, Phys. Lett. B 575, 242 (2003); Fl. Stancu, Phys. Lett. B **595**, 269 (2004).
9. R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91**, 232003 (2003).
10. E. Hiyama, M. Kamimura, A. Hosaka, H. Toki and M. Yahiro, Phys. Lett. B **633**, 237 (2006) [arXiv:hep-ph/0507105].