International Journal of Modern Physics A

STRUCTURE OF LIGHT AND HEAVY PENTAQUARKS *

Fl. STANCU

Physics Department, University of Liege ,
Sart Tilman, B-4000 Liege 1, Belgium

Light and heavy pentaquarks are described within a constituent quark model based on a spin-flavor hyperfine interaction. In this model the lowest state acquires positive parity. The masses of the light antidecuplet members are calculated dynamically using a variational method. It is shown that the octet and antidecuplet states with the same quantum numbers mix ideally due to $SU(3)_F$ breaking. Masses of the charmed antisextet pentaquarks are predicted within the same model.

Keywords: Pentaquarks; constituent quark models; parity and spin.

1. Introduction

The pentaquarks have been discussed in the literature since more than 30 years. Light and heavy pentaquarks have alternatively been predicted and searched for. The present wave of interest came with the observation of a narrow resonance, called Θ^+, of mass $M \simeq 1540 \pm 10$ MeV and width $\Gamma < 25$ MeV, by the LEPS collaboration at the end of 2002 [1]. This was interpreted as a light pentaquark of content $uudd\bar{s}$ following the 1997 predictions of Diakonov, Petrov and Polyakov [2] (for some other pioneering work see [3]). The LEPS experiment has been followed by the observation of another narrow resonance, called Ξ^{--}, M $\simeq$ 1862 MeV, $\Gamma \simeq 18$ MeV, by the NA49 collaboration [4], interpreted as a pentaquark of content $ddss\bar{u}$ and supposed to be also a member of the antidecuplet of Θ^+. In March 2004 a narrow heavy resonance, $M \simeq 3100$ MeV, $\Gamma \simeq 12$ MeV, has been observed by the H1 Collaboration [5] and was interpreted as a heavy pentaquark of content $uudd\bar{c}$. The pentaquark Θ^+ needs more solid confirmation (see Ref. [6]) while the other observations remain much more controversial. (For a historical note on pentaquarks see e. g. [7])

2. Present Approaches

Presently there is a large variety of approaches to pentaquarks: the chiral soliton or the Skyrme model, the constituent quark model, the instanton model, QCD sum

*Plenary talk at the 10th International Symposium on *Meson-Nucleon Physics and the Structure of the Nucleon*, Beijing, August 29 - September 4, 2004.

rules, lattice calculations, etc. The main issues are the determination of spin and parity, the decay width, the splitting between the isomultiplets belonging to the same irreducible representation of $\mathrm{SU}(3)_F$ and the effect of representations mixing on the masses and widths of pentaquarks.

3. Constituent Quark Models

Here I shall refer to pentaqurk studies in constituent quark models only. The constituent quark models describe a large number of observables in baryon spectroscopy (masses, formfactors, decay widths, etc) and it therefore seems quite natural to look at its predictions for exotics. The most common constituent quark models have either a spin-color (CS) or a spin-flavor (FS) hyperfine interaction. One can also have a superposition of CS and FS interactions in the so-called hybrid models (see below).

4. Why the FS Model ?

The present talk focuses mainly on a dynamical study of the light pentaquark antidecuplet and the charmed antisextet based on the FS interaction. Details of this study can be found in Refs. [8,9,10]. The calculations are based on the model Hamiltonian of Ref.[11], which represents a realistic form of the more schematic model of Ref. [12]. Chronologically the model Hamiltonian [11] has been first applied to the description of heavy pentaquarks of both negative [13] and positive parity [8]. It turned out that the positive parity pentaquarks were much lighter (few hundreds of MeV) than the negative parity ones at a fixed $q^4\bar{Q}$ content, where $Q = c$ or b. The parity can be found by looking at the q^4 subsystem. The lowest negative parity state with spin $S = 1/2$ comes from a q^4 subsystem which has the structure $|[4]_O[211]_C[211]_{OC};[211]_F[22]_S[31]_{FS}\rangle$. This means that there is no orbital excitation and the parity of the pentaquark is the same as that of the antiquark. If one quark is excited to the p-shell which implies a positive parity for the pentaquark, the Pauli principle allows the q^4 subsystem to have the structure $|[31]_O[211]_C[1111]_{OC};[22]_F[22]_S[4]_{FS}\rangle$ in its lowest state. Although this state contains one unit of orbital excitation the attraction brought by the FS interaction when q^4 is in its most symmetric state $[4]_{FS}$ is so strong that it overcomes the excess of kinetic energy and generates a positive parity state much below the negative parity one.

Besides giving a good description of non-strange and strange baryon spectra, by bringing the Roper resonance below the first negative parity state and describing well other baryon properties (see e. g. Ref. [14]), the flavor-spin interaction has support from QCD lattice calculations on baryons which suggests that the observed level order of positive and negative parity is an effect of the lightness of the u and d quark masses. Moreover the flavor-spin is a symmetry consistent with the large N_c limit of QCD.

In CS models the lowest positive parity state for Θ^+, with one unit of orbital excitation has symmetry $[31]_{CS}$ in the relevant degrees of freedom. Even for this symmetry, which is the lowest allowed one, the hyperfine interaction is not strong enough to overcome the excess of kinetic energy, so that the lowest state acquires negative parity in realistic models [15]. For various reasons, hybrid models also favor negative parity [16].

5. The light pentaquark antidecuplet

In $SU(3)_F$ a pentaquark state, described as a $q^4\bar{q}$ system can be obtained from the direct product

$$3_F \times 3_F \times 3_F \times 3_F \times \bar{3}_F = 3(1_F) + 8(8_F) + 3(27_F) + 4(10_F) \\ + 2(\overline{10}_F) + 3(27_F) + 2(35_F)$$

which shows that the antidecuplet $\overline{10}_F$ is one of the possible multiplets. The $SU(3)_F$ breaking induces representation mixing. One expects an important mixing between octet members and antidecuplet members with the same quantum numbers. This holds for $I = 1/2$ and 1. The results for the mass spectra of $\overline{10}_F$ and 8_F pentaquarks and their mixing based on the model of Ref. [11] are shown in Fig. 1. Here, as in any other model including the chiral soliton, one cannot determine the absolute mass of Θ^+. This mass has been fitted to the presently accepted experimental value of 1540 MeV. Reasons to accommodate such a value are given in Ref. [9]. The pure $\overline{10}_F$ spectrum, Fig. 1a, can approximately be described by the linear mass formula $M = 1829 - 145Y$ where Y is the hypercharge. This result is compared to the antidecuplet spectrum of Ref. [2], Fig. 1c, where $M = 1829 - 180Y$, which implies larger spacing than in the FS model. Presently the level spacing in the chiral soliton model is estimated to be smaller [17], thus closer to the FS model result.

As a consequence of the $SU(3)_F$ breaking the representations $\overline{10}_F$ and 8_F mix and accordingly the physical states are defined as

$$|N^*\rangle = |N_8\rangle \cos\theta_N - |N_{\overline{10}}\rangle \sin\theta_N,$$
$$|N_5\rangle = |N_8\rangle \sin\theta_N + |N_{\overline{10}}\rangle \cos\theta_N, \tag{1}$$

for N and similarly for Σ. Fig. 1b shows the masses of the physical states $|N_5\rangle$ obtained from this mixing $\overline{10}_F$ and 8_F [10]. The mixing angles θ_N and θ_Σ are calculated dynamically in this approach, by using the coupling matrix element of $\overline{10}_F$ and 8_F. This has combined contributions from all the parts of the Hamiltonian which break $SU(3)_F$ symmetry: the free mass term, the kinetic energy and the hyperfine interaction, see Ref. [10]. Interestingly, the combined contribution leads in practice to an ideal mixing. One obtains $\theta_N \simeq 35.34^0$, as compared to the ideal mixing angle $\theta_N^{id} = 35.26^0$ and $\theta_\Sigma \simeq -35.48^0$ as compared to $\theta_\Sigma^{id} = -35.26^0$.

By the definition (1), $|N^*\rangle$ is the "mainly octet" state and $|N_5\rangle$ is the "mainly antidecuplet" state. From the calculated mixing angle it follows that the former is approximately 67 % octet and the latter 67 % antidecuplet. The above mixing angle implies that $\cos\theta_N \simeq \sqrt{2/3}$ and $\sin\theta_N \simeq \sqrt{1/3}$. Then, for example, for positive

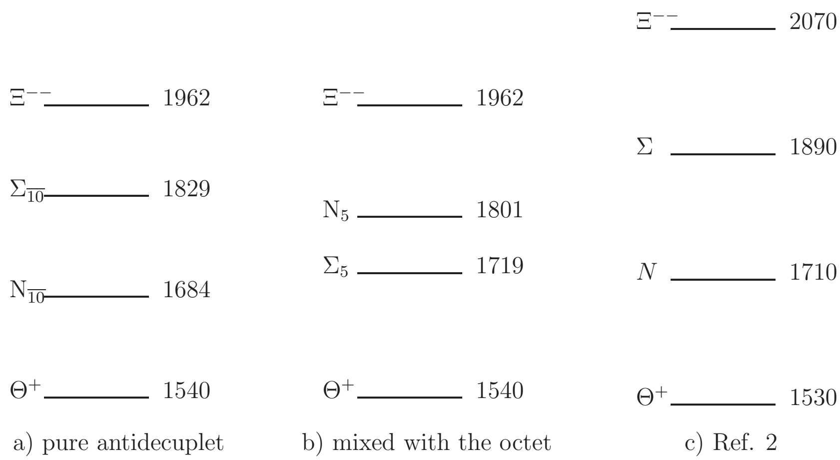

Fig. 1. The pentaquark antidecuplet masses (MeV) in the FS model: (a) pure antidecuplet and (b) after mixing with the pentaquark octet, as compared with the predictions (c) of the chiral soliton model Ref. 2.

charge pentaquarks with $I = 1/2$ one has

$$
\begin{aligned}
|N^*\rangle &\simeq \frac{1}{2}\,(ud-du)(ud-du)\bar{d}, \\
|N_5\rangle &\simeq \frac{1}{2\sqrt{2}}\,[(ud-du)(us-su)+(us-su)(ud-du)]\bar{s},
\end{aligned}
\qquad (2)
$$

i. e. the “mainly octet” has no strangeness and the “mainly antidecuplet” state contains the whole available amount of (hidden) strangeness.

The “mainly octet” nucleon state $|N^*\rangle$ acquires the mass $\mathrm{M(N^*)} \simeq = 1451$ MeV and for the “mainly octet” Σ state one obtains $\mathrm{M}(\Sigma^*) \simeq = 2046$ MeV. In the nucleon case this implies that there are two resonances in the Roper mass region: one which is obtained in the original calculations of Ref. [11] as a radial excited state of structure q^3 and mass 1495 MeV and the other the pentaquark state at 1451 MeV. A mixing of q^3 and $q^4\bar{q}$ could be a better description of the reality. There is some experimental evidence [18] that two resonances instead of one can consistently describe the $\pi - N$ and the $\alpha - p$ scattering in the Roper resonance region 1430 - 1470 MeV.

6. The charmed antisextet

In most models which accommodate Θ^+ and its antidecuplet partners, heavy pentaquarks $q^4\bar{Q}$ can be accommodated as well, being in principle more stable against strong decays than the light pentaquarks [19]. In an SU(4) classification, including charm, it has been shown [20] that the light antidecuplet containing Θ^+ and a charm antisextet with $\bar{s}$ replaced by $\bar{c}$ belong to the same SU(4) irreducible representation of dimension 60.

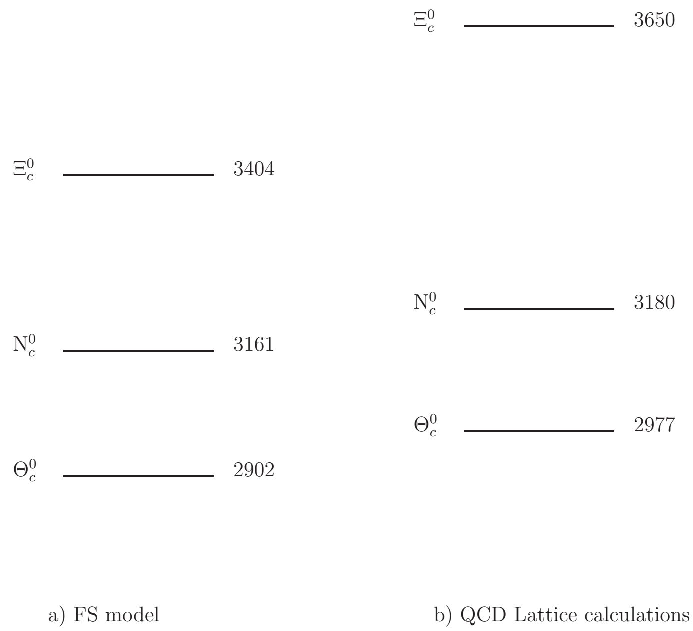

Fig. 2. The charmed pentaquark antisextet masses (MeV): (a) The FS model results of Ref. 8 and (b) QCD lattice calculations of Ref. 21.

The masses of the charmed antisextet calculated in the FS model [8] are presented in Fig. 2. They are compared to the only QCD lattice calculations [21] which predict positive parity for the lowest states. Although the two calculations have an entirely different basis the masses of Θ_c^0 of content $uudd\bar{c}$ $(I = 0)$ and of N_c^0 of content $uuds\bar{c}$ $(I = 1/2)$ are quite similar. Only for Ξ_c^0 of content $uuss\bar{c}$ $(I = 1)$ a mass difference of 250 MeV appears. However, by taking into account the lattice calculations numerical uncertainty of approximately $\pm$ 100 MeV, the two results look closer to each other. The experimental observation of charmed pentaquarks is contradictory so far. While the H1 collaboration [5] brought evidence for a narrow resonance at about 3100 MeV, there is null evidence from ZEUS or the CDF collaborations [22].

For an orientation, in connection to future experiments, it is interesting to calculate excited charmed pentaquarks Θ_c^{0*}. In the FS model used above the first excited state having $I = 1$ and $S = 1/2$ appears 200 Mev above Θ_c^0 which has $I = 0$. This supports the large spacing result obtained approximately in Ref. [23] for the FS model.

7. Conclusions

The recent research activity on pentaquarks could bring a substantial progress in understanding the baryon structure. It could help to shed a new light on some resonances difficult to understand, as e. g. the Roper or the $\Lambda(1405)$ baryon. The wave functions of such baryons may have substantial higher Fock components. Furthermore, in light hadrons it is important to understand the role of the spontaneous breaking of chiral symmetry, the basic feature of the chiral soliton model [2] which motivated this new wave of interest in pentaquarks. It is thought that the FS model used here has its origin in the spontaneous breaking of chiral symmetry as well [12]. An important common feature of the two models is that they both lead to positive parity for the light antidecuplet. If ever measured, the parity of Θ^+ could disentangle between various models. Also a clear theoretical understanding of the production mechanism of light and heavy pentaquarks is necessary. The experiments, which see or not see the pentaquarks, need a clear explanation.

Acknowledgments

I am most grateful to the organizers of the MENU04 Conference for their kind invitation and the excellent organization of this meeting.

References

1. T. Nakano et al., LEPS Collaboration, *Phys. Rev. Lett.* **91** 012002 (2003).
2. D. Diakonov, V. Petrov and M. Polyakov, *Z. Phys.* **A359**, 305 (1987);
3. D. Diakonov, hep-ph/0406043; D. Diakonov and V. Petrov, hep-ph/0409362.
4. C. Alt et al., NA49 Collaboration, *Phys. Rev. Lett.* **92**042003 (2004).
5. A. Aktas, H1 Collaboration, hep-ex/0403017.
6. T. Nakano, these proceedings.
7. Fl. Stancu, plenary talk MESON2004 Conference, Cracow, June 4-8 2004, hep-ph/0408042.
8. Fl. Stancu, *Phys. Rev.* **D58**, 111501 (1998).
9. Fl. Stancu and D. O. Riska, *Phys. Lett.* **B575**, 242 (2004).
10. Fl. Stancu, *Phys. Lett.* **B595** 269 (2004); ibid. Erratum, **B598**, 295 (2004).
11. L. Ya. Glozman, Z. Papp and W. Plessas, *Phys. Lett.* **B381**, 311 (1996).
12. L.Ya. Glozman and D.O. Riska, Phys. Rep. **268** (1996) 263.
13. M. Genovese, J. -M. Richard, Fl. Stancu and S. Pepin, *Phys. Lett.* **B425** 171 (1998).
14. D. O. Riska, these proceedings.
15. S. Takeuchi and K. Shimizu,hep-ph/0411016.
16. F. Huang, Z. Y. Zhang, Y. W. Yu and B. S. Zou, *Phys. Lett.* **B586**, 69 (2004).
17. J. Ellis, M. Karliner and M. Praszalowicz, hep-ph/0401127.
18. H. P. Morsch, P. Zupranski, *Phys. Rev.* **C61**, 024002 (1999), see also H. P. Morsch, these proceedings.
19. Fl. Stancu, *Few Body Syst. Suppl.* **10**, 399 (1999).
20. Bin Wu and Bo-Qiang Ma, *Phys. Rev.* **D70**, 034025 (2004).
21. T. -W. Chiu and T. -H. Hsieh, hep-ph/0404007, withdrawn from LANL several months after this conference was held. There is another lattice calculation of the mass of charmed pentaquarks, but it is restricted to Θ_c^0 only, which was found highly unstable and of negative parity (S. Sasaki, *Phys. Rev. Lett.* **93**, 152001 (2004)). The result is similar to that of Ref. [13] in the FS model. The parity of light pentaquarks is usually negative in QCD lattice calculations (see reviews by S. Sakaki, hep-ph/0410016 and by F. Csikor et al., hep-lat/0407033, see also T. T. Takahashi et al.,hep-lat/0503019) but

a clear evidence for a light pentaquark resonance is still an unsettled issue, as inferred for example from the work of K. Holland and K. J. Juge, hep-lat/0504007.

22. For recent experimental status see talks at the International Workshop PENTAQUARK04 held at SPring-8, July 20-23 (2004): www.rcnp.osaka-u.ac.jp/ penta04/.
23. K. Maltman, *Phys. Lett.* **B604**, 175 (2004) and these proceedings.