SOME PREDICTIONS, CALCULATIONS AND SPECULATIONS ON MULTIQUARK STATES

P. Sorba
CERN - Geneva, Switzerland

ABSTRACT

There is, maybe, strong experimental evidence in favour of a mesobaryonium $(4q,1\bar{q})$ state. Considering more than three flavours, there could be several stable dibaryons. The hidden colour in the deuteron could explain the amount of $\Delta\Delta$ isobar in it. These are the three points I would like to briefly discuss in this talk.

RESUME

Il existe peut-être une forte évidence expérimentale en faveur d'un état mesobaryonium $(4q,1\bar{q})$. Si l'on considère plus de trois saveurs, il pourrait y avoir plusieurs dibaryons stables. La partie couleur cachée du deutéron pourrait expliquer la quantité d'isobars $\Delta - \Delta$ qui y est contenue. Voici les trois points que je voudrais brièvement discuter dans ce séminaire.

INTRODUCTION

A certain excitement has been provoked these last two years by the narrow resonances found in the $p\bar{p}$ system as well as in formation experiments as in production experiments. The interpretation of such states as states made with two quarks and two antiquarks has reinforced the interest of high energy physicists in the problem of states made with more than three quarks, already suggested in 1968 by Rosner in the context of duality diagrams. Since the narrow states supposedly made with two quarks and two antiquarks have been called baryonium states, we have called mesobaryonium states the colour singlet states made with four quarks and one antiquark, while six quark states have been naturally called dibarvons[1].

It is these last two kinds of objects that I would like to discuss. From my work on the subject with H. Högaasen, I have selected three points which, I hope, will help show you why it is interesting and certainly very important to carefully study this new area of elementary particle physics. The results contained in the three following paragraphs are independent from each other. However, it is worthwhile to mention that the most important ingredient in these approaches is, as we will see, the notion of colour and the QCD.

1. MESOBARYONIUM: AN INTERESTING CANDIDATE

Considering systems of $4q$, $1\bar{q}$, an extension of the model proposed by Chan and Högaasen[2] for baryonium states has been studied. After briefly recalling the theoretical characteristics of such states, we will emphasize the recent discovery by the ACNO group[3] of a narrow enhancement in the $\Sigma^- K^+ \bar{K}^o$, mass spectrum at 2.58 GeVLc^2: this resonance is a very plausible candidate for a state $(udss\bar{s})$ appearing in the multiplet of our model at a mass of 2.61 GeV/c^2.

Let us consider a high-spin system of $4q$, $1\bar{q}$ as constituted by two subsystems Θ and D separated by an angular momentum L, each sub-system being separately in an s wave state[4]. Among the different possibilities which occur, two of them are the most susceptible of being associated to rather stable states: they are $\Theta = 3q$, $D = q\bar{q}$ where Θ and D are colour octets, and $\Theta = qq\bar{q}$, $D = qq$ with Θ and D antisextet and sextet of colour, respectively, the total state ΘD being, of course, a colour singlet. As for baryonium states, a simple consideration of colour leads to different families of states, with different properties (different decays, different masses, and so on). Note that the experimental discovery of colour isomers, which cannot be considered in the case of usual mesons and baryons, would be a proof of the colour degree of freedom! The determination of the spectrum of such states is based on the following two assumptions:

i) the masses of the Θ or D "pseudo" states are split by the interactions between the quarks in Θ or D due to colour exchange.

ii) the Θ-D states linked by the angular momentum L are assumed to fall on Regge trajectories where the slope is dependent on the colour of the sub-system Θ (or D) following the MIT bag model approach[5],

$$L = \alpha_o + \alpha'_c M^2 \tag{1}$$

Note that the slope α'_c includes all contributions of the classical colour field to the energy of the system when the spin of the quarks is neglected. We have $\alpha'_{c=8} = 0.6\ (\mathrm{GeV/c})^{-2}$ while $\alpha'_{c=6} = 0.57\ (\mathrm{GeV/c})^{-2}$. Now let us recall that interactions due to colour gluon exchange can be separated into two parts: the spin-dependent (colour-magnetic) part and the spin-independent (colour-electric) one. There are good reasons for believing that the colour-magnetic interaction is short-ranged and, if so, perturbation theory applies because of asymptotic freedom. Let us recall that the masses of the s wave baryons (qqq) and mesons ($q\bar{q}$) states are very well explained by the one-gluon exchange interaction[6]. So, let us first consider the Θ (or D) sub-system. The spin-spin interaction between two quarks, i and j, can be written:

$$V_{ij} = - C_{ij}\, \underline{\lambda}_i\, \underline{\lambda}_j\, \vec{\sigma}_i\, \vec{\sigma}_j \tag{2}$$

where C_{ij} is proportional to the gluon coupling constant α_s and depends on the overlap of the quark wave functions, and where $\underline{\lambda}$ and $\vec{\sigma}$ are the usual Gell-Mann and Pauli matrices.

Now, let us consider the total Θ-D states. The colour singlet states of spin S, with S belonging to the decomposition of the SU(2) product of representations: $S_\Theta \times S_D = |S_\Theta - S_D| + \ldots + |S_\Theta + S_D|$ where S_Θ and S_D are respectively the spin of the Θ and D sub-systems, are a priori not eigenstates of the total Hamiltonian, because of the gluon exchange between the quarks (or quark-antiquark). But gluons do not carry flavour. Therefore, because of the Pauli principle they cannot flip the colour of a sub-system without also flipping the spin. It follows that the spin-independent part of the Hamiltonian is diagonal in the states under consideration. Moreover, if magnetic forces are short-ranged their effect should decrease rapidly with L: this assumption is well verified for classical $q\bar{q}$ mesons. It results from these arguments that for high values of L, which correspond to the states of interest, the states Θ-D should be approximate eigenstates of the Hamiltonian.

Using a non-relativistic mass formula of the type:

$$M = \sum_q m_q + \langle H'_{\mathrm{magnetic}} \rangle \tag{3}$$

for s wave states, it appears reasonable from classical hadrons to use for C_{ij}

of formula (2) an average value $\bar{c} \simeq 20$ MeV as far as only up and down quarks are considered. In the case of one strange quark interacting with a non-strange one, C is closer to 12.5 MeV. We have used the approximation that all coefficients are equal to $\bar{c} = 15$ MeV in our mass estimates. This corresponds to neglecting the Σ-Λ mass difference of 78 MeV, and this number gives the kind of accuracy we believe exists today in our mass predictions. For the effective quark masses, we have used $m_{u,d} = 360$ MeV and $m_s = 535$ MeV.

As far as three flavours are considered, it is now a group theoretical exercise to construct the SU(3) flavour multiplets with their quark content, their corresponding spin, and the mass defect corresponding to $\langle H'_{magnetic} \rangle$.

Considering the colour octet bonded states, it appears that the lightest $4q, 1\bar{q}$ states with $L \neq 0$ are the states $L = 1$ belonging to the flavour-spin representation [F = 9, S = 3/2] corresponding to the configuration $\Theta^1(8,2)D^9(8,3)$ if the subscript in Θ or D refers to the flavour while the two numbers inside the bracket are relative to the colour and spin representation. These states have by far the greatest defect due to $\langle H'_m \rangle$. When these calculations were in progress last spring, we had as possible candidates two narrow peaks; the first one at 2.13 GeV/c^2 seen in the $\Lambda\pi\pi$ effective mass at the ISR[7], and the second one at 2.26 GeV/c^2 with $I = 1$, $Y = 0$ decaying into $\Lambda\pi\pi\pi$ [8] and $\Sigma\omega$ [9].

Assuming the state 2.26 GeV/c^2 to be a member of a flavour nonet with $L = 1$, $J^P = 5/2^+$ (recall total angular momentum $\vec{J} = \vec{L} + \vec{S}$) allows us to determine the intercept $\alpha_o = -2.19$ of the Regge trajectory:

$$L = -\,2.19 + 0.6\,M^2 \tag{4}$$

Such a normalization by the 2.26 GeV/c^2 state allows us to fix the masses of the other members of the flavour nonet [9, 3/2], $L = 1$. Moreover, Eq. (4) allows us to draw the Chew-Frautschi plot of states. A study of such trajectories can yield an -- at least qualitative -- expectation of the state decays in another colour octet bonded state by emission of a light meson. One can see, for example, that the $Y = 0$ states with no hidden $s\bar{s}$ pairs in the family [9, 3/2] have no open s wave pion emission channel. A more complete study leads to the conclusion that the most narrow states are to be found in the [9, 3/2] trajectory and in another trajectory denoted [72, 5/2]. Then the above discussion justifies the choice of the flavour nonet [9, 3/2] with $J^P = 5/2^+$ for the states 2.13 and 2.26 GeV/c^2. (As already mentioned, we believe the order of magnitude in the uncertainty of our mass predictions to correspond to the Σ-Λ mass difference). In this flavour nonet, there is an isosinglet $Y = 0$ partner containing a hidden $s\bar{s}$ pair. Because of its quark content $udss\bar{s}$, its dominant decay mode would be into three strange particles and its mass should lie around 2.26 GeV/c^2.

Last summer, in the analysis of the final state $\Sigma^- K^+ \bar{K}_1^o \pi^o$ produced in $K^- p$ interactions at 4.2 GeV/c, a narrow ($\Gamma \simeq 40$ MeV/c^2) enhancement in the $\Sigma^- K^+ \bar{K}_1^o$ mass spectrum at a mass of 2.58 GeV/c^2 has been observed by the ACNO collaboration[3]. We therefore think that mesobaryonium states have been discovered. A last question remains concerning the isospin of this $(\Sigma^- K^o \bar{K}_1)$ state. If its isospin is not I = 0 but I = 1, it will be possible to include this state in a multiplet [27, 3/2] L = 1 of colour antisextet-sextet bonded states. However, we think that the prettiest picture would emerge if the observed states are octet bonded.

$D^9 \Theta^1$

[3/2,9] states

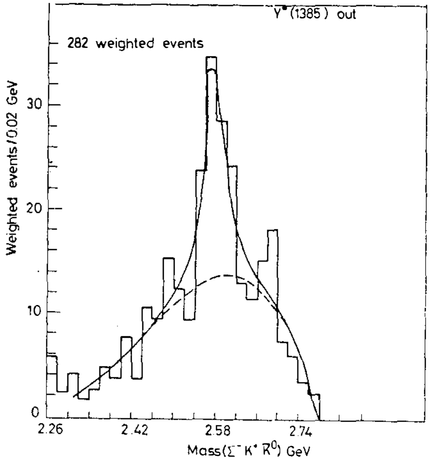
NO HIDDEN $s\bar{s}$ PAIR

M = 2.26 GeV	$udds\bar{u}$	$uds\bar{n}\bar{n}$	$udsu\bar{d}$	Y = 0
M = 2.43 GeV	$udss\bar{u}$	$udss\bar{d}$		Y = -1

HIDDEN $s\bar{s}$ PAIR

M = 2.43 GeV	$udsd\bar{s}$	$uuds\bar{s}$	Y = 1
M = 2.61 GeV	$udss\bar{s}$		Y = 0

Quark content for the nonets $\Theta^1 D^9$ of the colour octet bonded states. Masses are given for the lowest lying L = 1 [9, 3/2] with $J^P = 5/2^+$. Taking care of the magic mixing we have separated the states with hidden $s\bar{s}$ pairs from the others.



The $(\Sigma^- K^+ \bar{K}^o)$ mass distribution in the reaction $K^- p \to \Sigma^- K^+ K_1^o \pi^o$ at 4.2 Gev/c. Events in the $Y^*(1385)$ mass region have been excluded. The curve is the result of a fit to the histogram of an incoherent superposition of a relativistic Breit-Wigner function and a second order polynomial.

2. POSSIBLE EXISTENCE OF SEVERAL S WAVE STABLE DIBARYONS

Jaffe, looking at the mass defects due to gluon exchange forces for a 6q state in the framework of the MIT bag model, concluded that there existed a six-quark dihyperon (uuddss) light enough to be stable against strong interactions[10].

Considering the form of the colour magnetic interaction where, in a first step, the symmetry breaking effects have been neglected:

$$< H'_m > \; = \left[48 - \frac{1}{2}\, C_6(cs) + \frac{4}{3}\, S(S+1)\right] \bar{C} \tag{5}$$

it clearly appears that the greater is the value $C_6(cs)$ of the quadratic Casimir operator for the colour-spin $SU(6)^{cs} \supset SU(3)^c \times SU(2)^s$, the stronger is the bonding.

If we look at all the possible flavour-spin-colour configurations for six quarks in the s wave, satisfying the Pauli principle as far as three flavours only are involved, it appears that the biggest value of $C_6(cs)$ is relative to the 490 dimensional $SU(6)^{cs}$ representation, the Young tableau of which is and $C_6(490) = 144$. The corresponding $SU(3)_F$ flavour multiplet is then a singlet . Evaluating corrections due to the $SU(3)_F$ breaking $(m_{u,d} \neq m_s)$, Jaffe found that one could expect this state $J^P = 0^+$ to be stable with a mass of 2150 MeV/c^2. Note that the Brookhaven-Princeton collaboration did not find any narrow structure for H in the missing mass spectrum of the reaction $pp \to K^+K^+X$, however, two other experiments looking for H are in progress now.

Now, let us ask the following question: what can we say if we increase the number of flavours? The answer is quite interesting[11]: if the number of flavours is greater than three, then only two new F.C.S. configurations can be added to the previous set of representations. These are the 840 and 1134 dimensional SU(6) representations with Young tableaux and respectively to which correspond the $SU(n)_F$, $n > 3$, representations and . Moreover, looking at the values of $C_6(cs)$ we find: $C_6(840) = 144 = C_6(490)$ and $C_6(1134) = 160 > C_6(490)$! Therefore it could be worthwhile, considering the case $F = 4$, to consider more carefully the dibaryons supposed to belong to the corresponding $\overline{10}$, 10 and 6 dimensional $SU(4)_F$ representations respectively. (Note that the tableau is an SU(3) singlet but an SU(4) antidecuplet). For such a calculation the effects of $SU(4)_F$ symmetry breaking must be determined as precisely as possible. Estimates of the coefficients C_{ij} can be given; however, the complete evaluation of $< H'_m >$ involving fractional parentage coefficients proved to be too complicated in specific cases, and only limits can be set in general.

If, to estimate the stability of such states, we use the MIT bag mass formula, we will find that the 26 states of the $\overline{10}$, 10 and 6 $SU(4)_F$ representations appear as bound dibaryons. But the conclusions are quite different if we choose a mass formula of the form given in Eq. (3). Let us note that this last mass formula is linear in the number of quarks, while the first one depends on $N^{3/4}$. Therefore it usually gives heavier multiquark states than the MIT bag model mass formula. However, because of the uncertainty in the coefficients C_{ij} as soon as charmed quarks are involved, there remains some hope for certain of these states to appear as bound states. This is in particular the case of the lightest state (ududsc) in the sextet. Even with the mass formula of Eq. (3) this state could be stable against the decay into Λ(nns) and C_o(cnn).

3. HIDDEN COLOUR AND $\Delta\Delta$ ISOBARS IN THE DEUTERON

As far as dibaryons are concerned, one can ask how well-known states as deuteron can be considered in the framework of a 6q system. Comparing experimental data on deuteron form factor at large q^2 [12] with the predictions of dimensional quark counting rules[13], Matveev and I suggested that there is a possibility of a tunnelling transition of the real deuteron into a 6q s wave state with a probability of 7%. Therefore the deuteron state could be written as a superposition of a proton-neutron state and a 6q s wave state.

$$|d\rangle = \alpha\,|p - n\rangle + \beta|6q\text{-s wave bag}\rangle \tag{6}$$

with $\alpha^2 = 93\%$ and $\beta^2 = 7\%$, the spherical part $|6q\text{-bag}\rangle$ being affected in the same quantum numbers as the deuteron, i.e., $S = 1$, $I = 0$. Of course, the above description automatically reproduces the nuclear physics predictions of the deuteron. In particular, it lets simply appear the existence of an amount of $\Delta\Delta$ isobar constituent in $|d\rangle$, these isobars being contained in the $|6q\text{-bag}\rangle$. Using Clebsch-Gordan coefficients of the group $SU(12) \supset SU(3)_{colour} \times SU(2)_{spin} \times SU(2)_{isospin}$, as well as the Pauli principle, it is possible to decompose the 6q state into a $|3q\rangle|3q\rangle$ basis. The 3q, or baryon states, present in this decomposition are either in a singlet or in an octet of colour, i.e.:

$$|6q - s\text{ wave bag}\rangle = \sqrt{0.2}\,|B^1\text{-}B^1\rangle + \sqrt{0.8}\,|B^8\text{-}B^8\rangle \tag{7}$$

A detailed calculation of the $|B^1\text{-}B^1\rangle$ part led us to conclude that the deuteron can be seen as constituted by about 93.8% of p-n, 0.6% of $\Delta\Delta$ and 5.6% of "hidden colour", this last part corresponding to $|B^8\text{-}B^8\rangle$.

Very recently, with Högaasen and R. Viollier[14], we have considered in more detail this hidden colour part, and first calculated that it contained about 14% of $\Delta^8_{1/2} - \Delta^8_{1/2}$ and 86% of $N^8_{1/2}N^8_{1/2}$ and $N^8_{3/2}N^8_{3/2}$, if we use Δ^8_J and N^8_J to denote the isospin 3/2 and 1/2 systems of spin J. Imagining the emission of a gluon from a Δ^8 towards another Δ^8, this gluon could provoke a decolouration of the pair $\Delta^8_{1/2} - \Delta^8_{1/2}$ into a pair $\Delta^1_{3/2} - \Delta^1_{3/2}$, and in the same way transforms the pairs $N^8_{1/2}N^8_{1/2}$ or $N^8_{3/2}N^8_{3/2}$ into $N^1_{1/2}N^1_{1/2}$ pairs. But it is reasonable to think that the emitted gluon will not reach the second B^8 partner without creating quark-antiquark pairs. Then one can think that the Δ^1-Δ^1 part coming from Δ^8-Δ^8 will be seen in an inclusive experiment, as well as the Δ^1-Δ^1 fraction coming from the B^1-B^1 part, but not in an exclusive experiment where only the Δ^1-Δ^1 coming from B^1-B^1 will be taken into account. From our calculations the amount of $\Delta\Delta$ susceptible to be measured in an inclusive experiment would be (0.6 + 0.8)% = 1.4%, i.e., more than twice the $\Delta\Delta$ fraction (0.8%) coming from only B^1-B^1. Looking now at the experimental situation[15] it effectively appears that the amounts of $\Delta\Delta$ isobars found in deuteron varies following the considered spectator isobar experiment is a quasi-elastic one or an exclusive one. If in general, these exclusive reaction experiments agree for the $\Delta\Delta$ isobars to be in the range 0.4 - 0.9%, the (only) high energy inclusive experiment of Benz and Söding[16] who studied the reaction $\gamma d \to \Delta^{++}(1232)$ + anything gives 3.1%! If future experiments confirmed that the percentage of spectator-like Δ's is greater in inclusive than in two-body break-up reactions this would be a signature for the existence of colour non-singlet $|3q\rangle$ systems in the deuteron.

REFERENCES

1) For a recent review on the subject, see, for example: H. Högaasen and P. Sorba, Proc. of the Conf. on Hadron Physics at High Energies, Marseille (1978) eds. C. Bourrely, J.W. Dash and J. Soffer.

2) Chan Hong-Mo and H. Högaasen, Phys. Lett 72B, 121 (1977); Nucl. Phys. B136, 401 (1978).

3) ACNO Collaboration, submitted to Tokyo Conference (1978).

4) H. Högaasen and P. Sorba, Nucl. Phys. B145, 119 (1978); M. de Crombrugghe, H. Högaasen and P. Sorba, CERN preprint TH. 2537 (1978), submitted to Nucl. Phys. B.

5) K. Johnson and C. Thorn, Phys. Rev. D13, 1934 (1976).

6) A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D12, 147 (1975).

7) W. Lockman et al., Saclay preprint DPhPE 78.01 (1978).

8) W. Lockman et al., UCLA preprint 1109 (1978).

9) ACNO Collaboration, cited by R.A. Salmeron in Proc. European Conf. on Part. Phys., Budapest 1977 (eds. L. Jenik and I. Montway).

10) R.L. Jaffe, Phys. Rev. Lett. 38, 195 (1977), Erratum, 617 (1977).

11) H. Högaasen and P. Sorba, Nucl. Phys. B150, 427 (1979).

12) R.G. Arnold et al., Phys. Rev. Lett. 35, 776 (1975).

13) S. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1173 (1973); V.A. Matveev, R.M. Muradyan and A.N. Tavkhelidze, Lett. Nuovo Cim. 7, 719 (1973).

14) H. Högaasen, P. Sorba and R. Viollier, in preparation.

15) H.T. Weber and Arenhövel, Phys. Reports 36C, 277 (1978).

16) P. Benz and P. Söding, Phys. Lett. 52B, 367 (1974).