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A LOWER LIMIT ON THE EFFECTIVE MASS OF VALENCE GLUONS IN BARYONS

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ABSTRACT

To explain the results of a P matrix analysis of $\bar{K}N$ scattering data we invoke the effects of one gluon quark antiquark annihilation. The sign of the resulting force is then giving a lower limit on the mass of valence gluons in baryons.

Dedicated to Professor H. Wergeland on the occasion of his 70th birthday

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Hadronic spectroscopy is generally well understood when one assumes that mesons are made of quark-antiquark pairs and baryons of three quarks.

Inside QCD one would expect states that are more complex. Not only is there place for the mesons and baryons that we get by adding extra $q\bar{q}$ pairs to the usual configurations but one would also expect to see states with valence gluons.

There has indeed been great excitement about the possibility that glueballs i.e. colour singlet states made up of two colour octet gluons have already been observed[1].

In this letter we shall not be able to present any direct evidence fo states with valence gluons but we shall try to give a lower limit on the effective gluon mass in baryons. Our assumption will be that there are s wave multiquark states observed, either as primitives or as resonances, and from the experimental fact that the hypercharge zero isovector state is heavier than the corresponding isoscalar $J^P = 1/2^-$ state we shall deduce a lower mass for the qqqG states.

Let us take the least controversial view, namely that multiquark s-wave states can be seen as primitives[2]: due to colour confinement the wave function of the quarks in the hadron vanishes at a certain (bag) radius R. In the collision of two hadrons it is then natural to look for states which reflect this vanishing of the internal wave function at a distance b between the CM coordinates of the two hadrons. This is done with the P (or F) matrix which has poles when the radial wave function vanishes at a predetermined value of r i.e. r = b. The S matrix is defined by separating the wave function in outgoing and incoming waves and taking the ratio of their coefficients. The P matrix on the other hand is defined by separating the wave function in parts that do not vanish for r = b and parts that do vanish for r = b and taking the ratio of their coefficients. This is (in the elastic case) equivalent to define $P(E) = \frac{1 + F(E)}{b}$ by the logarithmic derivative of the wave function at the point r = b : $\left.\frac{u'_\ell(r,E)}{u_\ell(r,E)}\right|_{r=b} = P(E)$

Here P(E) is the P matrix[2], F(E) Feshbach and Lomons F matrix[3] and $u_\ell(r,E)$ is the solution of the radial Schrödinger equation.

The P matrix is of course determined by the S matrix and vice versa. A pole in the P matrix at a definite energy $E = E_b$ then signals that the wave function vanishes at a radius r = b and this vanishing can have a dynamic origin. It can reflect the confinement mechanism of the coloured quarks and if this is so the value of b that gives us information about confinement should lie between R and 2R where R is the bag[4] radius of a single hadron bag. Jaffe and Low suggest to use a value b = 1.4 R and show that the values of the energy where the corresponding P matrix for $\pi\pi$ scattering has poles indeed correspond to energy eigenstates as calculated in the MIT bag[4].

This is very interesting indeed, because it gives a signature even for states that are so shortlived that they are practically part of the continuum. In the case when resonances are narrow and the phase shift rapidly varying, the poles in the S and P matrix are at almost the same energy. There is today probably no genuine multiquark meson state seen in the S matrix, but in the P matrix they show their signature as poles, both in the nonexotic and exotic sector.

The P matrix analysis has also been done in the dibaryon sector[5] and in the meson-baryon sector[6].

This last case is of particular interest for us. Roiesnel[6] has analysed the KN, πN and $\bar{K}N$ elastic scattering and found rather good correspondence between poles in the P matrix and bag model eigenstates for the $Q^4\bar{Q}$ system in an overall s wave with $J^P = 1/2^-$.

One disagreement however is striking.

Whereas the bag model[7-9] predict the lowest $Y = 0$ $J^P = 1/2^-$ $I = 1$ and $I = 0$ states Σ_5 and Λ_5 to be degenerate, the experimental analysis find that Σ_5 is (at least) 90 MeV heavier than Λ_5, the mass of Λ_5 in the P matrix analysis is 1.45 GeV. One could believe – and one of us did so – that this is easily understood because there is an effective flavour symmetry breaking in the colour magnetic interaction. This is the elegant explanation[10] of the Σ-Λ mass difference in the $J^P = 1/2^+$ Q^3 sector.

Numerically $M_\Sigma - M_\Lambda = 75$ MeV and this is of the same order that is necessary to explain the $\Sigma_5 - \Lambda_5$ mass difference in the $J^P = 1/2^-$ $Q^4\bar{Q}$ sector that we discussed. Unfortunately an explicit calculation[11,12] shows that even allowing for flavour symmetry breaking in th olourmagnetic interaction the mass degeneracy of Λ_5 and Σ_5 persist. As Λ_5 and Σ_5 fall in the same flavour multiplet it would be awkward to invoke that big differences in the spatial wave function give this mass difference. We are therefore forced to seek another explanation and this is readily at hand.

In multiquark states there is often an interaction between a quark and an antiquark of the same flavour which is absent in ordinary mesons, namely the annihilation potential[13,14] originating from $Q\bar{Q}$ annihilation into a single gluon. In mesons which are $Q\bar{Q}$ colour singlets this force (which has its QED analogue in the ^3S repulsive annihilation potential of positronium) is necessarily absent, since the gluon transforms under the eight dimensional representation of SU_3^{colour}. In $Q^2\bar{Q}^2$ mesons and $Q^4\bar{Q}$ baryons there is however often a component of the wave function where $Q\bar{Q}$ pairs form a colour octet, flavour singlet $J^P = 1^-$ subsystem, and pair annihilation will induce a force which should have observable effects. Tentative phenomenological[13-15] applications of this genuine quantum field effect for gluons has been given for high mass baryons and for $J^P = 0^+$ $Q^2\bar{Q}^2$ mesons. For $Q^2\bar{Q}^2$ mesons this gives the desirable mixing[13-15] of states with and without hidden strangeness ($s\bar{s}$ pairs) that explains how $\delta(980)$ and $S^*(980)$ can have similar couplings to $\pi\pi$ and $K\bar{K}$ channels[2]. Indications are that the annihilation potential is attractive but the analysis is rather messy and complicated. In the s wave $Q^4\bar{Q}$ sector we have an ideal system to explore the annihilation force by analysing how it influences the two states Λ_5 and Σ_5.

It clearly has to be such that Σ_5 is becoming heavier than Λ_5. We should note that this result which is based on the P matrix analysis of $\bar{K}N$ scattering is true also if we assume (but not believe) that $Q^4\bar{Q}$ states show up as resonances (in the S matrix). There are $J^P = 1/2^-$ $Y = 0$ $I = 0$ states at 1405 MeV and 1670 MeV well below the lightest corresponding $J^P = 1/2^-$ $Y = 0$ $\Sigma(1750)$ [16].

To begin we shall restrict our model Fock-space to $Q^4\bar{Q}$ states, and only at the end make some comments to what happens if we include discrete Q^3G states where Q^3 is a colour eight QQQ system and G is a valence gluon.

The colour magnetic Hamiltonian over colour spin space is

$$H_{CM} = -\sum_{i>j} C_{ij}\, \sigma_i\sigma_j\, \lambda_i\lambda_j$$

where σ_i and λ_j are the generators of spin and colour transformations of particle i. The summation is over all pairs of particles (quarks and antiquark) in the hadron. The coefficients are equal in the flavour symmetry limit, with flavour symmetry breaking we distinguish the interaction between nonstrange-nonstrange (qq), nonstrange-strange (qs) and strange-strange (ss) quarks. Typical values of the coefficients C_{ij} that we use are: $C_{qq} \equiv C_o = 18$ MeV, $C_{qs} \equiv C_1 = 11$ MeV, $C_{ss} \equiv C_2 = 7$ MeV.

In the case where we use as a basis magically mixed flavour states for $Y = 0$ $J^P = 1/2^-$ $I = 0$ and 1 H_{CM} is represented by a 5×5 matrix[11,12] which in the flavour symmetric limit reduces to a 2×2 dimensional matrix. (This is for states where there is no hidden strangeness, they form the lowest lying states in this flavour sector.)

The matrices for relevant $I = 0$ and $I = 1$ states are identical so all five $I = 0$ energy eigenstates for $qqqs\bar{q}$ states with $J^P = 1/2^-$ are degenerate with an appropriate $I = 1$ state.

When annihilation is included we get an additional piece in the Hamiltonian H_A and $qqqs\bar{q}$ and $qqss\bar{s}$ states will mix, making our invariant model space 12 dimensional for Σ_5 like states, 9 dimensional for Λ_5 states. As in ref. 13) we define the action of the annihilation potential on colour octet spin 1 $Q\bar{Q}$

states to be

$$H_A|Q\bar{Q}\rangle = \begin{bmatrix} B_o & B_o & B_1 \\ B_o & B_o & B_1 \\ B_1 & B_1 & B_2 \end{bmatrix} \begin{bmatrix} u\bar{u} \\ d\bar{d} \\ s\bar{s} \end{bmatrix}$$

If the gluons had been free massless particles we should have a direct parameter free analogy with the Pirenne annihilation potential in positronium and $B_i = 6\ C_i$ where C is the strength parameter in the colour magnetic Hamiltonian[13]. For a bound (confined) gluon however, depending on whether the gluon mode has a smaller or larger effective mass than the $Q\bar{Q}$ pair the annihilation interaction is repulsive or attractive[14,15] ($B_i > 0$ or < 0). We therefore express B_i as $B_i = \alpha\ C_i$ and let α vary to study the effect of the annihilation on the states Λ_5 and Σ_5. The result for the lowest lying Λ_5 and Σ_5 states is shown on fig. 1 where the Λ_5 mass has been normalized to 1,45 GeV which is the energy where the I=0 Y=0 P matrix has a pole. From the figure it is obvious that annihilation has to be attractive. This is in agreement with the earlier estimates. Moreover, if $M(\Sigma_5) - M(\Lambda_5) \approx 100$ MeV $B_i \approx -3C_i$ and for nonstrange quarks then $B_o \approx -60$ MeV. This is therefore even quantitatively the same value that was favoured in an analysis of 0^+ $Q^2\bar{Q}^2$ mesons and baryons colour isomers[13,14].

As we said before, the attractive annihilation shows that the effective gluon mass M(G) in a baryon is greater than the effective mass of a $q\bar{q}$ pair which is ≈ 720 MeV. We therefore have the inequality $M(G) > 750$ MeV, a result that does not seem unreasonable.

To be sure that we do not make a preposterous claim, the same problem was repeated in a different manner.

The model Fock-space was enlarged[17] to include three discrete states Q^3G with valence gluons G both for isospin 0 and 1. The annihilation term H_A now has first order matrix elements between the $Q^4\bar{Q}$ and Q^3G subspaces whereas the colourmagnetic and mass terms have $Q^4\bar{Q}$ and Q^3G as two invariant subspaces. Diagonalization of the 15×15 $I = 1$ and 12×12 $I = 0$ energy matrices was done for a varying effective gluon mass and the result was as follows:

For a very low effective gluon mass $M(G) < 500$ MeV the lightest states both for $I = 0$ and $I = 1$ were mainly Q^3G states with little mixing of $Q^4\bar{Q}$ components. The lowest $I = 0$ state was always lighter than the lowest $I = 1$ state. For the states where the $Q^4\bar{Q}$ component was dominant the situation was quite different.

The lowest Λ_5 state was below the lowest Σ_5 state only if the effective mass of the valence gluon was bigger than 800 MeV.

As the P matrix poles found in $\bar{K}N$ scattering occurs at energies that correspond quite closely to the energy of $Q^4\bar{Q}$ states it would surprise us enormously if they are the result of Q^3G states. If they indeed are mainly $Q^4\bar{Q}$ states our earlier conclusion is therefore unchanged.

To summarize then: if the P matrix pole in the $I = 0$ $\bar{K}N$ scattering amplitude is due to a $Q^4\bar{Q}$ state and not a Q^3G state the effective mass of the gluon in a baryon has to be bigger than 750-800 MeV. The lowest Q^3G state is therefore heavier than 1500 MeV.

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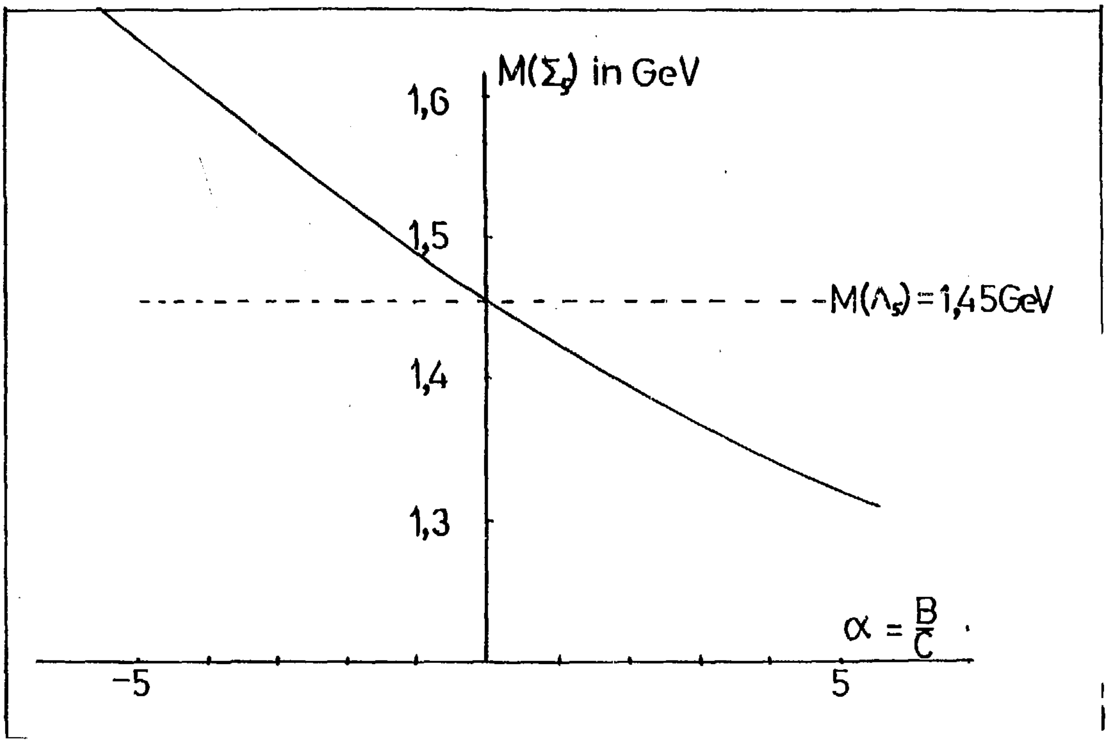
FIGURE CAPTION

Fig. 1 The mass of Σ_5 as the annihilation contribution varies. Λ_5 is normalized to be at 1,45 GeV.



M(Σs) in GeV
1,6
1,5
1,4
1,3
M(Λs) = 1,45GeV
α = B/C
−5
5