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PERHAPS A STABLE DIHYPERON*

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ABSTRACT

In the quark bag model the same gluon exchange forces which make the proton lighter than the Δ(1236) bind 6 quarks to form a stable, flavor singlet (strangeness -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant mass plots. Production and decay systematics of the H are discussed.

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The possibility that hadrons may be described by a confined color gauge theory of quarks and gluons has attracted great interest recently.[1] The bag model[2,3] provides an adaptation of these ideas to conventional spectroscopy. The S-wave baryons (Q^3) and many features of the S-wave mesons ($Q\bar{Q}$) are remarkably well described by the model in terms of four parameters of relatively fundamental significance.[3] Furthermore the model may be applied to any S-wave multiquark system ($Q^m \bar{Q}^n$, $n + m > 3$) without additional parameters. It offers the hope of answering long-standing questions regarding the nature and experimental elusiveness of exotics.[4,5]

Here I wish to point out that the same model applied to the Q^6 system predicts the existence of certain relatively light dihyperons one of which may be stable. Specifically, the model predicts an S-wave flavor singlet dihyperon (H) with $J^P = 0^+$ at 2150 MeV. With this mass the H must decay weakly. The model also predicts a light S-wave dibaryon flavor octet with $J^P = 1^+$. The $I = Y = 0$ member of the octet (H*) at 2335 MeV may appear as a bound state of $\Sigma\Sigma$ decaying strongly into $\Lambda\Lambda$ or $N\Xi$. Other members of the octet and all other dihyperons are unbound.

These are single hadrons, not loosely bound S-wave states of two baryons like the deuteron. As yet no such states are known. Besides the deuteron the only well documented dibaryon is the Λp enhancement at 2128 MeV.[6] Long ago Oakes[7] observed that such a state might be expected as the SU(3) brother of the deuteron ($Y = 1$ member of a $\underline{\overline{10}}$). Its proximity to ΣN threshold is appropriate to a loosely bound state of two baryons. Whether this is in fact the origin of the 2128 enhancement is as yet uncertain.

Consider a fixed number of quarks and antiquarks in a bag, all in the ground state and altogether forming a color singlet. The ordering of states is dictated by the color magnetostatic interaction between quarks.[3,8] Because of it, 0^- mesons are lighter than 1^- mesons; $1/2^+$ baryons are lighter than $3/2^+$ baryons. The effects of this interaction are summarized in simple spectroscopic rules analogous to Hund's rules of atomic spectroscopy.[5] The existence of these dihyperons would be striking confirmation of the underlying color gauge theory and the bag-dynamical framework in which it is imbedded.

In the quark-bag model S-wave quarks carry three labels: color ($SU(3)_c$); flavor ($SU(3)_f$—charm is irrelevant to these considerations); and the SU(2) generated by relativistic, positive parity, $j = 1/2$ quarks, to which we refer loosely as "spin." It is advantageous to combine color and spin to form "colorspin" ($SU(6)_{cs}$). The quarks (and antiquarks) must be antisymmetrized in colorspin and flavor since they all occupy the same spatial state. The only physical hadrons are overall color singlets. $SU(3)_f$ violations are induced by giving the strange quark a small mass (m_s = 279 MeV) while the u and d quarks are kept massless.

The contribution to our S-wave hadron's mass from lowest order gluon exchange is proportional to

$$\Delta \equiv -\sum_{i>j} \vec{\sigma}_i \cdot \vec{\sigma}_j \, \vec{\lambda}_i \cdot \vec{\lambda}_j \, M(m_i R, m_j R) \qquad (1)$$

where $\vec{\sigma}_i$ ($\vec{\lambda}_i$) is the spin (color) vector of the i-th quark normalized to 3(2). $M(m_i R,\ m_j R)$ measures the interaction strength. In the bag model it is a simple function[3] of the quark masses (m_i) which induces further, small SU(3) violations.

For color singlet hadrons containing only quarks (no antiquarks)

$$\Delta = \left(8N - \frac{1}{2} C_6 + \frac{4}{3} J(J+1)\right) \bar{M} \qquad (2)$$

where N is the total number of quarks, J is their angular momentum, and C_6 is their "colorspin"—the quadratic Casimir of SU(6) for the colorspin representation of the quarks. For the moment we set $m_s = 0$ $\left(\overline{M} \equiv M(0,0)\right)$. In this limit the mass of a hadron is given by a simple formula:

$$M = \frac{4}{3}(4\pi B)^{1/4}\left[2.043\,N - z_0 + \alpha_c\,\Delta\right]^{3/4} \tag{3}$$

where $B^{1/4} = 146$ MeV, $z_0 = 1.84$ and $\alpha_c = g^2/4\pi = 0.55$ are fixed in the $Q\overline{Q}$ and Q^3 sectors of the model.[3]

Equation (2) is a special case (no antiquarks) of the interaction studied in Ref. 5. The rules of Ref. 5 are trivial in this case: the lightest dibaryons will be those in which the quarks are in the colorspin representation with the largest possible Casimir (the eigenvalues of C_6 are much greater than $8/3\,J(J+1)$ for the states of interest). Large Casimirs are associated with symmetric colorspin representations. Antisymmetry requires the flavor representation of light dibaryons to be largely antisymmetric—consequently of low dimension. This connection is evident in the accompanying table listing the S-wave states of 6 quarks. Colorspin representations are listed by their dimension. Antisymmetrization determines the flavor multiplet corresponding to each colorspin. Only color singlets are physical states. The angular momentum of the color singlets in each colorspin multiplet is listed in the table. The mass is given in the limit $m_s = 0$.

Most of the "states" listed in the table probably do not correspond to particles or resonances. Consider, for example, the deuteron channel $(I = 0,\ S = 1)$. The lightest 6-quark bag with deuteron quantum numbers is in the $\overline{10}$ at 2165 MeV, 288 MeV heavier than p and n alone. This object is classically unstable against small deformations leading to fission into separate n and p bags. The appropriate quantum variables are those of the separate n and p. Quantizing about the 6-quark object would lead to instabilities analogous to those in a field theory with negative squared-mass. Once the n and p coordinates are viewed as the important quantum variables, the 6-quark object would appear to be evidence for a repulsive core in the n-p interaction (a la the Born-Oppenheimer treatment of H_2).[9] Thus we expect three possibilities: (1) A 6-quark state lighter than all baryon decay channels is clearly stable; (2) A 6-quark state above all dibaryon decay thresholds is probably evidence of a short-range repulsion in the channels to which it couples; (3) A 6-quark state above some decay thresholds but below others would appear as a resonance (bump) in the open channel much like the Λ (1405) below $\bar{K}p$ threshold appears in $\Sigma\pi$. Notice that we are unable to say anything about the long-range baryon-baryon force on the basis of the bag model. Weakly bound states like the deuteron may escape our notice.

Only the $\underline{1}$ and $\underline{8}$ in the table are light enough to be bound or resonant. SU(3) violation is essential—all the dibaryons in the $\underline{1}$ and $\underline{8}$ are strange. Equation (1) may be evaluated without approximation by techniques analogous to the fractional parentage expansion of nuclear physics. The flavor singlet is found at 2150 MeV. The $I = Y = 0$ state in the octet (H*) is found at 2335 MeV. Other members of the octet are found at 2395-2465, 2220-2230, and 2480-2505 MeV for the $I = 1$, $Y=+1$ and $Y = -1$ members, respectively. The uncertainties in these masses arise because certain fractional parentage coefficients prove too difficult to calculate. Only the H and H* are bound with respect to two baryon channels. The $Y = 1$ state has the quantum numbers of the Λp enhancement at 2128 MeV. As noted by Hepp[6] the effect which appears at 2128 MeV may be due to a pole as much as 100 MeV higher in mass. At present it is not possible to decide whether the Λp enhancement is a deuteron-like state or the $I = 1/2$, $Y = 1$ member of our dibaryon octet. For the remainder of the paper we consider only the H and H*.

To bracket the possibilities we consider four possible mass ranges for the H:

(1) $M(H) < 2055$ MeV; (2) $2055 < M(H) < 2230$; (3) $2230 < M(H) < 2380$; (4) $M(H) > 2380$ MeV. In case 4 the H is above all two-baryon thresholds to which it couples strongly. It represents therefore a repulsive interaction in all two-baryon channels to which it couples. It is improbable that the bag mass calculation is so much in error that case 4 applies. In case 3 the H is a $\Sigma\Sigma$ bound state (or if $M(H) < 2260$ MeV also a $N\Xi$ bound state) decaying strongly into $\Lambda\Lambda$. It would appear as a bump in $\Lambda\Lambda$ invariant mass plots (in, e.g., $\Xi p \rightarrow \Lambda\Lambda$). Were the H very light (case 1), it would be stable except against double weak decay ($H \rightarrow nn$). Cases 1 and 3 are not favored by the bag mass estimates but must be retained as possibilities in light of the crude nature of the model.

The model predicts the mass to lie well within the range covered by case 2. For this region the H would decay predominantly by weak nonleptonic decay to two baryons. The more conventional nonleptonic decay involving a pion ($H \rightarrow BB\pi$) is forbidden if $M(H) < 2195$ MeV, and is probably unimportant over the mass range of interest. Assuming the nonleptonic weak Hamiltonian to be octet-dominated, the three-two baryon decay channels are related by SU(3): $H \rightarrow \Sigma^- p : \Sigma^o n : \Lambda n = 6:3:1$. The effects of S-wave phase space on the branching ratios are not too drastic if $M(H) = 2150$ MeV: $B(H \rightarrow \Sigma^- p) = 0.5$, $B(H \rightarrow \Sigma^o n) = 0.3$ and $B(H \rightarrow \Lambda n) = 0.2$. As the H-mass decreases toward 2055 MeV, the Λn mode comes to dominate. The $\Sigma^- p$ signature is much clearer than Λn. If the Λn mode dominates, the H will be more difficult to see.

The nonleptonic weak decay of the H may be somewhat inhibited if H^{NL}_{weak} is octet-dominated. According to the table, there is no $0^+\underline{8}$ 6-quark state with all the quarks in the ground state. H^{NL}_{weak} must promote a quark to an excited S-wave $0^+\underline{8}$ configuration which subsequently fissions into two baryons. Excited S-wave 6-quark bags are much heavier than the H. It is difficult to put a number on this effect because of our ignorance of H^{NL}_{weak}. The H may be expected to live somewhat longer than the Σ^- or Λ (which are connected to members of the same flavor multiplet by H^{NL}_{weak}).

Production of the H requires strangeness -2 exchange. Part or all of this may be broken up in the choice of beam. Production by protons provides a clean signature: $pp \rightarrow HK^+K^+$. The H itself need not be seen since any mass less than 2230 MeV recoiling against two positive kaons would be unambiguous. Either a bubble chamber or counter experiment is possible. This process has the further advantage of mapping out the $\Lambda\Lambda$ mass spectrum whether or not the H (and/or H*) is found.

Other possible production mechanisms include $\Lambda p \rightarrow HK^+$, $\Sigma^- p \rightarrow HK^o$, $\Xi^- p \rightarrow H\pi^o$ and $K^- d \rightarrow HK^o$, $K_L d \rightarrow HK^+$. Any mechanism involving neutral kaons admits a large dineutron background because of K^o, $\overline{K}^o$ mixing.

The dynamics of the H* are similar to those of the H in mass range 3. We expect it to show itself as a bump in $\Lambda\Lambda$ invariant mass plots at approximately 2335 MeV.

At present data on dihyperon channels are meager. Low statistics dilambda mass spectra[10] seen in Ξ^- or K^- capture on nuclei show one or two bumps below $\Sigma\Sigma$ threshold. Nuclear rescattering effects tend to wash out any structure. At least one[11] and perhaps another[12] doubly strange hypernuclei are known from emulsion experiments. In these events a Ξ is apparently captured on a light emulsion nucleus causing it to fragment into an ordinary nucleus and a double hyperfragment (e.g., $_{\Lambda\Lambda}He^6$) which is identified by successive emission of π^- as the two Λ's decay. Were the two hyperons bound as an H in the nucleus, double π decay would be forbidden (M(H) < 2193 MeV) or at least inhibited (M(H) > 2193 MeV). Either M(H) > 2193 MeV or nuclear effects are such that at least one Λ decays before reacting to form an H. Further experiments on proton (or deuteron) targets are necessary to settle the matter.

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TABLE I

$SU(6)_{cs}$ Representation	C_6	J	$SU(3)_f$ Representation	Mass in the limit $m_s = 0$
490	144	0	$\underline{1}$	1760
896	120	1, 2	$\underline{8}$	1986
280	96	1	$\underline{10}$	2165
175	96	1	$\underline{\overline{10}}$	2165
189	80	0, 2	$\underline{27}$	2242
35	48	1	$\underline{35}$	2507
1	0	0	$\underline{28}$	2799