Nonuniversality of the bag constant *B* and the dilambda stability problem

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In the quark bag model with a nonuniversal constant B, the dihyperon H lies above the $\Lambda\Lambda$ threshold. The possible value of B for a six-quark system is estimated on the basis of data on the magnetic moment of the deuteron.

The quark bag model is known to give a good description of the static properties of the mesons $\bar{q}q$ and the baryons qqq (Ref. 1). A generalization of this model to dibaryon $6q$ systems leads to the prediction of a dihyperon H or a dilambda with a mass of 2.15 GeV (Ref. 2), which would lie 80 MeV below the $\Lambda\Lambda$ threshold and which would decay through a weak interaction. Although the data available on double hypernuclei[3] do not support this prediction and indicate $m_H > 2.219$ GeV, interest in the possibility of a long-lived H particle has recently increased significantly in connection with the suggestion[4] that this particle might be the source of the signal from the Cygnus X-3 pulsar (but see Ref. 5). Our purpose in the present letter is to show that when we allow for the nonuniversality of the constant B, which characterizes the external pressure of the quantum-chromodynamics (QCD) vacuum on the quark bag, the H particle turns out to be a short-lived particle, since it lies above the $\Lambda\Lambda$ threshold.

The predictions of the quark bag model are usually constructed under the assumption that B is universal for all hadrons. The value of B is fixed on the basis of a description of the low-lying states of mesons and baryons; the most typical values of this constant are $(130\text{–}150\ \text{MeV})^4$. A strong indication that B is not universal follows from the QCD sum rules[6] and, in particular, from the fact that the energy density of the physical vacuum, $\epsilon_0 = -(9/32)\langle 0|(\alpha_s/\pi)G^a_{\mu\nu}G^a_{\mu\nu}|0\rangle = -(240\ \text{MeV})^4$, is significantly larger than B. The inequality $B < |\epsilon_0|$ means that in the simplest hadrons there is an incomplete suppression of the nonperturbative fluctuations of the QCD vacuum.

It is natural to suggest that B increases with increasing density of the color charges in the hadron. For a bag of n quarks we would have $R \sim n^{1/4}$ and $n/V \sim n^{1/4}$, so that according to this hypothesis we would expect B_n to increase with increasing number of quarks in the bag: $B_2 < B_3 < B_6 \ldots$. This hypothesis was used in Ref. 7, where the spectra of light mesons and baryons were described with different constants B_2 and B_3; the relations $B_2 < B_3 < |\epsilon_0|$ were in fact found.

To evaluate B_6/B_3, we impose the restrictions on the admixture of the $6q$ bag in the deuteron which follow from data on the magnetic moment of the deuteron, μ_d, and which were derived in our earlier paper.[8] If the wave function of the deuteron (in the S-wave) has an admixture of a $6q$ bag with a probability P_B, then μ_d is changed by an amount[9]

$$\delta\mu_d^{(B)} = P_B(\mu_B - \mu_p - \mu_n), \tag{1}$$

where μ_p, μ_n and μ_B are the magnetic moments of the proton, the neutron, and a bag with the quantum numbers of the deuteron, $^3S_1$. On the other hand, even if we make the relativistic corrections, we are left with a discrepancy between the prediction of the nucleon model of the deuteron and experimental data[9]:

$$\delta\mu_d = \mu_d^{\rm theo} - \mu_d^{\rm expt} = (0.5 - 1.0)\times 10^{-2}\mu_0 ,$$

where $\mu_0 = e\hbar/2m_p c$. If we attribute this entire discrepancy to an admixture of a $6q$ bag, then using $\mu_B = 1.2\mu_0$ and the Reid soft-core model for the NN component we find[8] $P_B \approx 3\%$ The quantity P_B determined in this manner has the meaning of an upper limit on the admixture of the $6q$ bag in the deuteron.

Let us compare P_B with the probability that two nucleons will be at a distance less than b:

$$\overline{P}_B = P_S - \int |\psi_{NN}^{(s)}(\mathbf{r})|^2 \,\theta(r - b) d^3\mathbf{r}, \tag{2}$$

where P_S is the normalization of the S-wave. The quantity b is usually linked with the radius of the $6q$ bag by the relation $b = 1.12R_{6q}$ (Ref. 10, for example). For the radius $R_{6q} = 1.32$ fm, corresponding to the MIT bag model,[1] we find $\overline{P}_B = 15\%$, i.e., a result five times P_B. This contradiction is extremely discouraging, since in the hybrid model of the deuteron (in which the structure of the deuteron at $r > b$ is described by an NN component, while that at $r < b$ is described by the $6q$ MIT bag) we find[1)] $P_B \approx \overline{P}_B$ [1)].

If we treat the radius of the $6q$ bag as an adjustable parameter, we can eliminate this contradiction by reducing R_{6q}. In the MIT bag model, we can assume[8] $\mu_B = (\mu_p + \mu_n)R_{6q}/R_{3q}$. Now expressing P_B in terms of $\delta\mu$ and the ratio R_{6q}/R_{3q} with the help of (1), and equating it to the quantity $\overline{P}_B$ given by (2), we find an equation for R_{6q}. If we use the approximate formula $\overline{P}_B = 0.22b - 0.18$, which holds for the Reid soft-core model in the interval 0.9–1.6 fm, the equation which we are seeking takes the form

$$\frac{R_{6q}}{R_{3q}} = 1 + \frac{2}{R_{3q}}\left[\left((\overline{P}(3q))^2 + \frac{\delta\mu_d}{\mu_d}R_{3q}\right)^{1/2} - \overline{P}(3q)\right], \tag{3}$$

where R_{3q} and R_{6q} are expressed in femtometers. With $R_{3q} = 1$ fm, we find from the equation of Ref. 3 the result $\xi = R_{6q}/R_{3q} = 1.12$. In this case we have $P_B = \overline{P}_B \approx 9.2\%$.

If the constant B is universal, i.e., if $B_6 = B_3$, we find $\xi_0 = R_{6q}/R_{3q} = 1.32$. Since $R \sim B^{-1/4}$, a decrease in the ratio ξ can be achieved by increasing the constant B_6 in accordance with

$$R_{6q}/R_{3q} = 1{,}32\,(B_3/B_6)^{1/4}. \tag{4}$$

The solution of Eq. (3) with $R_{3q} = 1$ fm corresponds to such an increase in the constant B_6:$B_6 = 1.93B_3$.

TABLE I.

Model		m_H GeV	R_H GeV^{-1}	$m(^3S_1)$ GeV	$R(^3S_1)$ GeV^{-1}
MIT	$B_6 = B_3 = (146\ \text{MeV})^4$	2.15	6.19	2.16	6.58
	$B_6 = 1.93\, B_3$	2.46	5.25	2.54	5.58
QB-ITEP	$B_6 = B_3 = (132\ \text{MeV})^4$	2.02	7.11	2.03	7.47
	$B_6 = 1.81\, B_3$	2.29	6.14	2.35	6.44
CBM $R_{3q} = 1.06$ fm	$B_6 = B_3 = (133\ \text{MeV})^4$	2.10	6.95	2.08	7.31
	$B_6 = 1.82\, B_3$	2.37	5.96	2.40	6.23
CBM $R_{3q} = 0.84$ fm	$B_6 = B_3 = (154\ \text{MeV})^4$	2.34	5.99	2.23	6.14
	$B_6 = 1.86\, B_3$	2.66	5.08	2.58	5.21

The predictions of the MIT bag model are known to be improved by the introduction of a pion cloud around the bag (this configuration corresponds to the so-called chiral bag model or CBM). We have also carried corresponding calculations on the ratio $\eta = B_6/B_3$ in the chiral bag model; we found $\eta_{\text{CBM}} = 1.86$ and 1.82 for $R_{3q} = 0.84$ and 1.06 fm. Corresponding calculations in the ITEP model,[7] with corrections for the center-of-mass motion, yield $B_6/B_3 = 1.81$. Consequently, from the restrictions on the admixture of the 6q bag in the deuteron we find $B_6/B_3 > 1.8$ in all the models considered by us.

An increase in the constant B substantially changes the predictions of the bag model regarding the possible existence of a bound dilambda state and regarding stable strange quark matter.[12] Table I shows the results of calculations of the masses and radii of the H particle and of the 6q $^3S_1$ resonance according to the various quark models: the MIT model,[1] chiral-bag model (CBM),[13] and the ITEP model.[7] We see that in all the models considered here the dilambda is not bound at $B_6/B_3 > 1.8$. By increasing the constant B, we increase the mass of the dilambda to 270–320 MeV. This mass is considerably larger than the magnitude of the hadron shift estimated in Ref. 14.

We might also note that for the MIT model without pion corrections we find $B_6^{1/4} > 170$ MeV in our case. According to calculations by Farhi and Jaffe,[12] for such values of B, the strange quark matter is unstable at a zero pressure. Such matter can exist only if there is a high external pressure, e.g., inside a neutron star.[15]

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[1)] We are ignoring the contribution from the transition region between the NN component and the bag. In principle, this region could be taken into account by the approach which was developed in Ref. 10 and which was used in Ref. 11 to describe μ_d. However, if we do not fix the form of the Hamiltonian in terms of quark variables, we are forced to make some additional assumptions regarding the contribution of the interior region to μ_d.

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