Can the H Dibaryon Survive Instantons?

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The effects of instanton-induced interactions on the H-dibaryon mass are studied. It is found that a strong three-body repulsion will result in a weakly bound or unbound H dibaryon with binding energy $\lesssim 10$ MeV.

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The H particle is a dibaryon which is stable against strong decays if its mass is below the $\Lambda\Lambda$ threshold. It is a flavor-singlet six-quark state, *uuddss*, with strangeness -2, and spin 0. A variety of valence quark models predict a rather deeply bound state for this system.[1,2] Its discovery would provide new and important information on the structure and dynamics of hadrons in low-energy QCD. Experimental searches are being made, but, as yet, there is no positive sign of such a deeply bound state.[3]

It was suggested that the magnetic part of the one-gluon-exchange interaction, called the color-magnetic interaction (CMI), is responsible for the H-particle binding. This is the same interaction that splits the pseudoscalar and vector mesons and the octet and decuplet baryons. It also yields a short-range repulsion between two nucleons due to the quark-exchange mechanism.[4] In the Breit-Fermi form, the central part of the CMI reads[5]

$$V_{\mathrm{CMI}} = -\frac{\alpha_s}{4}\sum_{i<j}\frac{2\pi}{3m_i m_j}(\lambda_i\cdot\lambda_j)(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\delta(\mathbf{r}_{ij}). \quad (1)$$

This interaction lowers the H-dibaryon mass by a few hundred MeV assuming that the strength α_s is determined phenomenologically by fitting the observed hyperfine splittings. Realistic model calculations of the H dibaryon have been done including effects of couplings to two-baryon states, meson-exchange contributions, the SU(3)-breaking effect, etc., and have predicted a bound state of binding energy 20–100 MeV below the $\Lambda\Lambda$ threshold.[6]

The value of α_s required above (1.3–2), however, is too large compared with the value predicted by QCD scaling [$\alpha_s(1\ \mathrm{GeV})\lesssim 0.5$]. Recently it has been pointed out that there is another source of hyperfine splitting (HFS),[7,8] i.e., the instanton-induced interaction (III), and that HFS is partly from the CMI and partly from the III. Thus the strength of the CMI may be reduced. Although the introduction of the III has little influence on the hadron spectra except for the η-η' splitting (and the pion mass through the chiral-symmetry breaking[9]), it gives strong repulsion for the H dibaryon. In Ref. 8, we demonstrated in a model calculation that the H dibaryon might disappear because of the strong three-body repulsion of the III. In this Letter, we make a more realistic estimate of the H mass considering meson-exchange contributions and maintaining consistency with the η-η' mass splitting.

The instanton, a nonperturbative gluon-field configuration with nontrivial topology, has provided a qualitative understanding of a variety of nonperturbative features of QCD. One of its important consequences is that the coupling of light quarks (u, d, and s) to the instanton breaks axial $\mathrm{U}(1)_A$ symmetry and causes the η-η' mass splitting. Recent attempts to build a quantitative model of interacting instantons conclude that the QCD vacuum may be an instanton liquid, consisting of strongly correlated instantons, whose size ρ_c is small, $\sim\frac{1}{3}$ fm, with density of one instanton or anti-instanton per fm^4 in four-dimensional Euclidean space, and that coupling of light quarks induces dynamical breaking of chiral symmetry. Thus the light quarks get effective (constituent) masses of a few hundred MeV.[9] It should be noted, however, that the instanton-quark coupling does not provide quark confinement. Confinement comes from a long-range nonperturbative correlation, while the instanton effects considered here represent short-distance correlations of the glue field. As usual, we have to add a long-range confinement force separately. The one-gluon-exchange interaction may be modified by the presence of instantons. But here we do not take the effect into account and leave it to future investigation.

It has been shown in Ref. 10 that the special role of the light-quark coupling to the instanton can be represented by a local effective interaction, i.e., the III, given by

$$\begin{aligned} H^{(3)} &= V_0\bar{\psi}_R(1)\bar{\psi}_R(2)\bar{\psi}_R(3)\,\tfrac{189}{40}\,\mathcal{A}_f\left[1-\tfrac{1}{7}\sum_{i>j=1}^{3}(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\right]\psi_L(3)\psi_L(2)\psi_L(1)+\mathrm{H.c.}\\ &= V_0\bar{\psi}_R(1)\psi_R(2)\bar{\psi}_R(3)[1+\tfrac{3}{32}(\lambda_1\cdot\lambda_2+\mathrm{perm})-\tfrac{9}{320}D_{123}+\tfrac{9}{32}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\lambda_1\cdot\lambda_2+\mathrm{perm})+\tfrac{27}{320}D_{123}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2+\mathrm{perm})\\ &\quad -\tfrac{9}{64}F_{123}(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot\boldsymbol{\sigma}_3]\psi_L(3)\psi_L(2)\psi_L(1)+\mathrm{H.c.}, \end{aligned} \quad (2)$$

where $\psi_{L(R)} \equiv \frac{1}{2}(1 \mp \gamma_5)\psi$ is the left- (right-) handed Dirac field operator, $\mathcal{A}_f \equiv \frac{1}{6}(1 - P_{12} - P_{23} - P_{31} + P_{123} + P_{132})$ (P_{ij}'s being flavor-exchange operators) is the projection operator to the flavor-singlet state of three quarks, $\boldsymbol{\sigma}$ is the SU(2) Pauli matrix, and λ is the SU(3) color operator of the quark. $D_{123} \equiv d_{abc}\lambda_1^a\lambda_2^b\lambda_3^c$ and $F_{123} \equiv f_{abc}\lambda_1^a\lambda_2^b\lambda_3^c$ are symmetric and antisymmetric color-singlet operators, respectively. The Hermitian-conjugate term (H.c.) arises from the interaction through the anti-instanton. This interaction, called the instanton-induced interaction, is locally gauge invariant, and also Lorentz covariant.

The three-body III, Eq. (2), (III3) induces a two-body interaction (III2) for valence quarks through contraction of a pair of $\bar{\psi}_R$ and ψ_L by the current quark mass term or by the vacuum quark condensate. The terms which remain after contraction read

$$\begin{aligned} H^{(2)} &= V_0^{(2)}\bar{\psi}_R(1)\bar{\psi}_R(2)\tfrac{15}{8}\mathcal{A}_f(1 - \tfrac{1}{5}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)\psi_L(2)\psi_L(1) + \text{H.c.} \\ &= V_0^{(2)}\bar{\psi}_R(1)\bar{\psi}_R(2)(1 + \tfrac{3}{32}\lambda_1\cdot\lambda_2 + \tfrac{9}{32}\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\lambda_1\cdot\lambda_2)\psi_L(2)\psi_L(1) + \text{H.c.}, \end{aligned} \tag{3}$$

where the strength of the two-body interaction $V_0^{(2)}$ is related to the three-body strength and the quark condensate of the third flavor,[9]

$$V_0^{(2)}(1,2) \equiv \tfrac{1}{2}V_0(\langle\bar{\psi}\psi\rangle - Km_3) = \tfrac{1}{2}V_0(-Km_3^{\text{eff}}). \tag{4}$$

K is a positive constant and depends on ρ_c. The ratio $\xi = V_0^{(2)}(u,s)/V_0^{(2)}(u,d)$ is given by $m_u^{\text{eff}}/m_s^{\text{eff}}$ [$\sim$0.6 (Ref. 9)]. Note that III2 is attractive, while III3 is repulsive, because $\langle\bar{\psi}\psi\rangle$ is negative. We take $\langle\bar{\psi}\psi\rangle = -(250\ \text{MeV})^3$.

In the instanton-liquid vacuum, the III, Eqs. (2) and (3), represent nonperturbative quark interactions with a short range ($\sim\rho_c$). It is important to find the role of the III on the hadron spectra and interactions. In our previous work,[8] we have applied the III to the valence quark model and studied phenomenological consequences. As we mentioned before, III2, Eq. (3), contains a spin-dependent term identical to the CMI, Eq. (1). We argued that the III may share a part of the hyperfine splitting of the hadron spectrum with the perturbative gluon-exchange interaction: (HFS) $= (1-p)$(CMI) $+p$(III). The ground-state baryon spectrum is independent of the ratio p of the III and the CMI except for an overall shift, provided that the total strength of the spin-spin interaction is fixed by the observed N-Δ mass difference. This is because III3 vanishes in a single baryon due to symmetry, and III2 has spin dependence identical to that of the CMI. The SU(3)-breaking effect is also very similar because the quark-mass dependence in the CMI gives the same ratio of the u-s and u-d spin-spin interactions, ξ. The ratio ξ in the CMI fitted to the baryon spectrum is the same as III2, i.e., 0.6. The ratio of s-s to u-u, ξ', in the CMI is very small, while ξ' in III2 vanishes.[11]

We also studied effects of the III on short-range baryon-baryon interactions using the quark-exchange model. We found an attractive direct force and a shorter-range exchange force due to III2. The exchange force is strongly repulsive for NN, but attractive for the H dibaryon. It is this attraction in H that makes a usual quark model give a deeply bound state. The most remarkable result is, however, that III3 yields a strong repulsion in the H dibaryon. The strength of the three-body repulsion is comparable to the two-body attraction in H and thus the bound H state tends to disappear when we turn on III3.

One of the key parameters to be determined is the share of the III in HFS, p. The baryon spectrum is insensitive to p, as we discussed above. However, because the III breaks $\text{U}(1)_A$ symmetry, the η-η' mass difference in the meson spectrum depends strongly on p. The observed mass splitting is 409 MeV. Using the observed value of the η_1-η_8 mixing angle, $\theta = -22.6°$ (the average of the values given by the $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ branching ratios[12]), one can estimate the contribution of the SU(3)-breaking effect to the η-η' mass difference. We estimate it to be $0.58m^{\text{eff}} \sim 222$ MeV for the nonrelativistic potential quark model with $m^{\text{eff}} = 384$ MeV, and $\sim$133 MeV for the bag-model wave function with a bag radius $R = 3.34\ \text{GeV}^{-1}$. The one-gluon exchange (OGE) also has a SU(3)-breaking term, but its contribution to the η-η' mass difference is small. It is about 41 MeV for the potential quark model and 48 MeV for the bag model, even when we take the large α_s with which OGE gives the whole N-Δ mass difference. Thus, one needs an extra contribution (about 150–230 MeV) to explain the observed η-η' mass difference. This is given by the III. We estimate by perturbation that the full III ($p = 100\%$) yields 428 MeV for the potential quark model and 784 MeV for the bag model for the splitting. From these values for the various contributions, we may determine the share of the III, $p \sim 38\%$ for the potential quark model and $p \sim 31\%$ for the bag model. It should be noted, however, that p is sensitive to the choice of θ and also to the size of η and η'.

We further argue that quenched lattice QCD calculations support a significant contribution of the III to HFS. It is known that these calculations yield the N-Δ mass difference too small, roughly $\frac{1}{2}$ of the observed value.[13,14] Although instanton gauge configurations may be available on the lattice, the coupling (2) will be suppressed in the present quenched lattice calculation because of rather heavy mass for light quarks and because of a lack of quark loops.[14] It is likely that the discrepancy comes from the III. In summary, we expect the value of p to be about 25%–60%, considering various uncertainties in the above estimates. We use three values for p, i.e., 0.25, 0.4, and 0.6, in the present calculation and compare the results. Correspondingly, the strength of the CMI is reduced by the factor $1-p$.

The MIT bag model gives a bound H particle with the binding energy 54 MeV. The attraction comes mainly from the CMI and the volume energy term. A perturbative estimate of the III with the same wave function gives about 45-MeV reduction of the binding energy. When the binding energy becomes small, the system will cluster, and the coupling of the H dibaryon to two-baryon states, $\Lambda\Lambda$-$N\Xi$-$\Sigma\Sigma$, becomes important. The coupling also causes SU(3) breaking due to the threshold differences among the three channels. In order to take the coupling effects into account, we employ the quark-cluster model[4] (QCM) with those three channels, $\Lambda\Lambda$, $N\Xi$, and $\Sigma\Sigma$, coupled.[11] Previous QCM analyses revealed that the meson-exchange interaction between the baryons significantly changes the H binding energy.[6] We emphasize that the meson-exchange contribution in the H particle must be determined in a way consistent with the baryon-baryon scattering. Here we consider a long-range pseudoscalar- (π,K) exchange potential and a phenomenological medium-range attraction. The latter is assumed independent of spin and flavor as is the scalar-exchange potential in conventional one-boson-exchange models. We use NN scattering to calibrate the medium-range potential:

$$V_\sigma(R)=v_\sigma\{\exp[-R^2/(a_\sigma-a_\sigma')^2]-\exp[-R^2/(a_\sigma+a_\sigma')^2]\}\,, \qquad (5)$$

where we assume $a_\sigma'=0.05$ fm, on which the results do not depend strongly. The overall strength v_σ and the range a_σ are fitted to the low-energy NN scattering phase shift at $E\lesssim 100$ MeV. The pseudoscalar exchange is regularized by the form factor of the baryon.[4] The parameters used here are $m_\pi=138$ MeV, $m_K=495.7$ MeV, and $g_{\pi NN}^2/4\pi=14.4$. The other coupling constants are determined by SU(3) symmetry.[15] We find that pseudoscalar exchange plays a lesser role in the H mass than scalar exchange. Because III2 yields a medium-range attraction which is approximately independent of the channel, the meson-exchange parameters v_σ, a_σ depend on the strength of the III, or on the share p. In QCM, the meson-exchange potentials are combined with the quark-exchange interaction kernels. The resonating-group-method equation reads

$$\left\{\frac{1}{\sqrt{N}}[K+(1-p)V^{\mathrm{OGE}}+pV^{\mathrm{III}}+V^{\mathrm{conf}}]\frac{1}{\sqrt{N}}+V^{\mathrm{meson}}\right\}\chi=E\chi\,, \qquad (6)$$

where N, K, V^{OGE}, V^{III}, and V^{conf} are resonating-group kernels, and χ is a relative-motion wave function. We take a linear two-body confining potential proportional to $\lambda_i\cdot\lambda_j$. As in Ref. 8, we take only the $(0s)^6$ shell-model state into account in evaluating III3.

We performed QCM calculations for the various sets of parameters given in Table I. The table shows the binding energy of H obtained for various values of the III to HFS ratio p, the size parameter of the quark cluster wave function, b, the strength v_σ and the range a_σ of the scalar potential, the ratio $(u\text{-}s)/(u\text{-}d)$ of color-spin interactions, ξ (the same value for both OGE and III2), and the ratio $(s\text{-}s)/(u\text{-}d)$, ξ' (only for OGE). For each parameter set, we determine ξ and ξ' so that the threshold-energy differences among $\Lambda\Lambda$, $N\Xi$, and $\Sigma\Sigma$ are reproduced. The calculation A contains no III, resulting in a bound state of H with a binding energy of 45 MeV. This is a typical quark-model prediction in the absence

TABLE I. The binding energy (B_H) of the H dibaryon from the $\Lambda\Lambda$ threshold in various parameter sets. Parenthesized values are resonance energies above the threshold. B_H' is the one without III3. For the other notations, see the text after Eq. (6).

Parameter set	A	B	C	C'	D
p	0	0.25	0.40	0.40	0.60
$(1-p)\alpha_s$	1.319	0.989	0.792	0.836	0.528
$pV_0^{(2)}$ (MeV fm^3)	0	−64.1	−102.5	−177.2	−153.8
pV_0 (MeV fm^6)	0	9.46	15.13	26.14	23.37
b (fm)	0.5	0.5	0.5	0.6	0.5
m^{eff} (MeV)	383.7	383.7	383.7	300.0	383.7
a_{conf} (MeV/fm)	95.05	84.55	78.26	55.23	69.87
ξ	0.6	0.6	0.6	0.6	0.618
ξ'	0.1	0.05	0.02	0.02	0
a_σ (fm)	0.63	0.72	0.84	0.89	1.55
v_σ (MeV)	1154.1	639.3	377.1	590.7	131.4
B_H (MeV)	45	1	(−20)	8	(−25)
B_H' (MeV)	45	46	51	65	81

of the III. If 25% of the N-Δ splitting is shared by the III, calculation B, then the bound state almost disappears. When we further increase p, calculation C ($p=40\%$), the bound state goes away. It still appears as a resonance 20 MeV above the $\Lambda\Lambda$ threshold but below the $N\Xi$ threshold. This resonance can be interpreted as a $N\Xi$ bound state coupled weakly to $\Lambda\Lambda$.

These results are subject to ambiguities in the parameter choice. They are especially sensitive to the size parameter b, because the ratio of III3 and III2 is proportional to $1/b^3$. The parameter set C', which has a larger size and smaller quark mass, brings the bound state back, but the binding energy is far less than for A, the case with no III. For each quark-model parameter set, the parameters of the scalar potential are fitted to the NN scattering phase shift by performing a QCM calculation for the NN system. However, it is not the differences in the scalar potentials that unbind the H particle. In fact, without III3, each parameter set gives a bound state with binding energy 46–81 MeV (see Table I).

We conclude that the strong three-body repulsion due to the light-quark–instanton coupling makes the H-dibaryon state unbound or, even if it is bound, barely bound. Our estimate suggests that the binding energy is less than 10 MeV, which is consistent with the presently available experimental limit for the H particle. A sizable contribution of the III to the hadron spectrum has just been recognized and we need further studies of its significance in other hadronic states as well as refinement of its effect on the H particle. Meanwhile, experimental H-dibaryon searches should continue for a better understanding of quark dynamics in the hadron mass spectrum and of the hadron-hadron interaction.

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