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Dihyperons in chiral color dielectric model

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Abstract. The mass of the dibaryon having spin, parity $J^{\pi} = 0^{+}$, isospin $I = 0$ and strangeness -2 is computed using chiral color dielectric model. The bare wave function is constructed as a product of two color-singlet three-quark clusters and then it is properly antisymmetrized by considering appropriate exchange operators for spin, flavor and color. Color magnetic energy due to gluon exchange, meson self energy and energy correction due to center of mass motion are computed. The calculation shows that the mass of the particle is 80 to 160 MeV less than twice Λ mass.

Keywords. Dihyperons; chiral color dielectric model.

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1. Introduction

The possibility of a dibaryon consisting of two u, two d and two s quarks was first considered by Jaffe [1]. This object is a singlet of color, flavor and spin and has maximum attractive color magnetic energy. Jaffe's MIT bag model calculation and the mass of this object, called dihyperon or H_1 particle, was predicted to be 2150 MeV (about 80 MeV less than twice Λ mass). Thus, H_1 can decay only by weak interactions. Later, the calculations of mass of H_1 have been refined by including center of mass correction [2], $SU(3)$-flavor symmetry breaking [3], surface energy term in the bag model [4], coupling of pseudoscalar meson octet [5] etc. Calculations have also been done in non-relativistic potential model [6–8] and Skyrmion model [9]. Most of these calculations predict that the mass of H_1 is close to twice Λ mass. We expect the H_1 particle to have a structure of six-quark object, unlike the deuteron which (from a number of experimental considerations) is a two-baryon object bound by exchange of mesons. The reason behind this argument is that the separation between two nucleons in deuteron is rather large and bulk of the binding of the deuteron can be explained by pion exchange interaction. This is not the case for H_1 since pion exchange is not possible between Λs and therefore the meson exchange is not expected to contribute significantly to H_1 binding.

The QCD allows existence of exotic color neutral objects such as glueballs, hybrids consisting of gluons as well as quarks and particles having baryon number greater than one. Whether such objects can be produced and whether these are stable or not is an interesting question and efforts are being made to observe such exotic baryons experimentally. It is therefore necessary to investigate their properties in different theoretical models as well. In the present work, we present a calculation of the mass of H_1 in chiral color dielectric

(CCD) model. In the following, in §2 we give a brief description of the CCD model, in §3 we describe how the computation of H_1 mass is done and in §4 we present the results and conclude.

2. The chiral color dielectric model

The CCD model Lagrangian density is given by [10]

$$\mathscr{L} = \bar{\psi}\left\{i\gamma_\mu\partial_\mu - \left(m_0 + \frac{m}{\chi}\left(1 + \frac{i}{f}\lambda_a^{\mathrm{f}}\phi^a + \frac{g}{2}\lambda_a^{\mathrm{c}}\gamma^\mu A_\mu^a\right)\right)\right\}\psi$$
$$+\frac{1}{2}(\partial_\mu\phi_a)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}\chi^4(x)(F_{\mu\nu}^a)^2 + \frac{1}{2}\sigma_v^2(\partial_\mu\chi)^2 - U(\chi), \quad (1)$$

where ψ, A_μ, χ and ϕ are quark, gluon, scalar (color dielectric) and meson fields respectively, m and m_ϕ are the masses of quarks and mesons, f is the pion decay constant, $F_{\mu\nu}$ is the color electromagnetic field tensor, g is the color coupling constant and λ_a^{c} and λ_a^{f} are the usual Gell-Mann matrices acting in color and flavor space respectively. The flavor symmetry breaking is incorporated in the Lagrangian through the quark mass term $(m_0 + (m/\chi)U_5)$, where $m_0 = 0$ for u and d quarks. So masses of u, d and s quarks are m, m_0 and $m_0 + m$ respectively. The meson matrix consists of η, π and K fields. The self interaction $U(\chi)$ of the scalar field is assumed to be of the form

$$U(\chi) = \alpha B\chi^2(x)[1 - 2(1 - 2/\alpha)\chi(x) + (1 - 3/\alpha)\chi^2(x)]$$

so that $U(\chi)$ has an absolute minimum at $\chi = 0$ and a secondary minimum at $\chi = 1$. The parameters of the CCD model are quark masses (m and m_0), the 'bag constant' (B), strong coupling constant ($\alpha_{\mathrm{s}} = g^2/4\pi$), pion decay constant ($f = 93$ MeV), dielectric field mass ($m_{\mathrm{GB}} = \sqrt{2\alpha B/\sigma_v^2}$) and the constant α in $U(\chi)$. These are fixed by fitting the properties of hadrons of baryon number one. Our earlier calculations [10] show that the octet and decouplet baryon masses are fitted by choosing m and $B^{1/4}$ between 100 and 140 MeV. The results are not sensitive to the value of α and we have chosen it to be 24.

The procedure for computing the dihyperon mass is similar to the method followed in the baryon spectroscopy computations [10,11]. Thus, we compute the equations of motion for quark and dielectric field and solve these in mean field approximation. The solutions are assumed to be spherically symmetric. This gives the bare dibaryon states and their energies. We then solve for the gluon Green function in the presence of the color dielectric field and using it, compute the color magnetic energy. We also compute the correction due to spurious center of mass motion. Next, we compute the coupling of pseudoscalar mesons to the dibaryon from the basic quark–meson coupling. Using this, we compute the energy contribution from the meson self energy. With this, the dibaryon mass is given by

$$M_B = \langle B(\vec{0})|H_0|B(\vec{0})\rangle + E_M + E_{\mathrm{meson}}(B), \quad (2)$$

where $\langle B(\vec{0})|H_0|B(\vec{0})\rangle$ includes the center of mass correction, E_M is the contribution due to color magnetic energy and $E_{\mathrm{meson}}(B)$ is the contribution due to meson self energy,

$$E_{\mathrm{meson}}(B) = \sum_{B',\phi}\int \mathrm{d}^3k \frac{\langle B|H_{\mathrm{int}}|B',\phi(\vec{(k)})\rangle\langle B',\phi(\vec{(k)})|H_{\mathrm{int}}|B\rangle}{M_B - E_{B'}(k) - \omega_\phi(k)}. \quad (3)$$

3. Dibaryon wave function

The wave function of the bare six-quark state is constructed from the $s_{1/2}$ quark wave functions. We have to ensure that the color wave function of this state is antisymmetric and the wave function should be antisymmetric under the exchange of any two quarks. It is convenient to start from a product of two color-neutral three-quark cluster wave functions and choose the spin-flavor wave functions such that the total wave function is antisymmetric with respect to the exchange of two quarks within the clusters. Actually, the wave function of each cluster is just the octet and decouplet baryon wave functions. We then antisymmetrize the product wave function with respect to the exchange of two quarks between two clusters. Thus the dibaryon wave function is $|c_1c_2\rangle_{\mathrm{f,s,c}} = \mathscr{P}\sum_{1,2}\alpha_{1,2}|c_1\rangle_{\mathrm{f}}|c_1\rangle_{\mathrm{s}}|c_1\rangle_{\mathrm{c}} \times |c_2\rangle_{\mathrm{f}}|c_2\rangle_{\mathrm{s}}|c_2\rangle_{\mathrm{c}}$ where the subscripts f, s, c denote the flavor, spin and color wave functions of three-quark clusters and c_1 and c_2 denote the first and second cluster respectively. $\sum_{1,2}$ includes the summation over possible spins, isospins and hypercharges of the clusters 1 and 2 so as to give a dibaryon state of definite spin, parity, isospin and strangeness. The permutation operator $\mathscr{P} = \frac{1}{\sqrt{8}}[1+\mathscr{S}^{\mathrm{c}}_{14}\mathscr{A}^{\mathrm{fs}}_{14}][1+\mathscr{S}^{\mathrm{c}}_{25}\mathscr{A}^{\mathrm{fs}}_{25}][1+\mathscr{S}^{\mathrm{c}}_{36}\mathscr{A}^{\mathrm{fs}}_{36}]$ is required for proper antisymmetrization of quark wave functions between two clusters. Note that since the color wave function of a cluster is a color singlet, we need to symmetrize intercluster color wave function and therefore antisymmetrize the spin-flavor wave function.

The dihyperon state we want to consider in this work is a color-flavor- and spin-singlet state. In terms of the cluster wave function described above, the spin-flavor-color wave function of the dihyperon is,

$$|H_1\rangle = \frac{1}{4}\mathscr{P}\{|p\Xi^-\rangle + |\Xi^- p\rangle - |n\Xi^0\rangle - |\Xi^0 n\rangle - |\Sigma^+\Sigma^-\rangle - |\Sigma^-\Sigma^+\rangle + |\Sigma^0\Sigma^0\rangle + |\Lambda\Lambda\rangle\}\{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\}|C_1\rangle_{\mathrm{c}}|C_2\rangle_{\mathrm{c}}, \quad (4)$$

where the first term on the right-hand side of eq. (4) consists of a combination of baryon octet flavor wave functions and the second bracket is the antisymmetric (two baryon) spin wave function. Note that the baryon wave functions themselves consist of the product of $SU(3)$ color and $SU(6)$ flavor-spin wave functions of quarks. It is straightforward to show that the wave function is a singlet of color, spin and flavor.

In order to compute the meson self energy, we need to know the wave functions of spin-1 flavor-octet dibaryons and their masses. In terms of these, the meson energy correction is

$$M_{\mathrm{meson}} = \frac{3}{2f_\pi^2\pi^2}\left[3\int\frac{k^4\mathrm{d}kv_\pi^2(k)}{\varepsilon_\pi(k)(M_0 - M_\Sigma - \varepsilon_\pi(k))} + 2\int\frac{k^4\mathrm{d}kv_K^2(k)}{\varepsilon_K(k)(M_0 - M_N - \varepsilon_K(k))} + 2\int\frac{k^4\mathrm{d}kv_K^2(k)}{\varepsilon_K(k)(M_0 - M_\Xi - \varepsilon_K(k))} + \int\frac{k^4\mathrm{d}kv_\eta^2(k)}{\varepsilon_\eta(k)(M_0 - M_\Lambda - \varepsilon_\eta(k))}\right]. \quad (5)$$

Here Ms are the masses of the dibaryon states excluding the meson self energy [12], $v(k)$ is the form factor for the meson coupling to the quark in the dibaryon states and $\varepsilon(k)$ is the energy of the respective meson.

Table 1. The dependence of dihyperon mass (M_0) on the parameters of the CCD model. α_s is dimensionless, the proton rms radius (column 6) is in units of fm, the proton magnetic moment (column 7) is in units of nuclear magneton and the masses are in units of MeV. The dihyperon mass is given in the last column.

m_{GB}	α_s	m_0	m	$b^{1/4}$	r_{rms}	μ_p	χ^2	M_H
819	0.269	103	211	103	0.781	2.44	4.32	2071
893	0.472	122	210	103	0.760	2.37	3.84	2073
927	0.288	108	212	108	0.751	2.37	4.37	2087
968	0.578	133	209	106	0.740	2.34	3.80	2083
1008	0.216	102	214	113	0.731	2.33	4.81	2103
1059	0.271	111	213	115	0.717	2.30	4.68	2109
1118	0.261	112	213	118	0.703	2.27	4.85	2119
1167	0.430	132	211	118	0.689	2.24	4.59	2121
1208	0.232	112	214	123	0.683	2.23	5.19	2133
1251	0.214	111	215	125	0.673	2.20	5.41	2140

4. Result and discussions

In the present calculation the dihyperon mass has been computed for a number of sets of the parameters which fit nucleon, Δ and Λ masses. For these sets, the difference between calculated and experimental masses of other octet and decouplet baryons are within few %. This is reflected in $\chi^2 = \sum_{\text{baryons}}(M_{\text{exp}} - M_{\text{th}}^2)/M_{\text{exp}}$ displayed in table 1. Thus, regarding the baryon masses, the quality of fit is similar for all the parameter sets considered. The proton rms radius and magnetic moment for these parameter sets have also been displayed. The table shows that the agreement with experimental value improves with the decrease in glueball mass.

The calculated dihyperon masses are displayed in the last column of table 1. One finds that the dihyperon mass increases almost linearly with the glueball mass and does not show any systematic dependence on the other parameters. Further, the variation in the dihyperon mass is quite large. For example, the dihyperon mass changes by about 70 MeV when the glueball mass is increased from about 800 MeV to 1250 MeV. This variation arising from the change in m_{GB} is about an order of magnitude larger than the variation found in the baryon octet and decouplet masses. Here we would like to note that the lower values of the glueball masses ($m_{GB} < 1$ GeV) yield better agreement with the static properties of baryons (charge radii, magnetic moments etc.) [10]. Furthermore, it has been observed that a better agreement with the πN scattering data is obtained for $m_{GB} \sim 1$ GeV or smaller [13]. We therefore feel that results with $m_{GB} \leq 1$ GeV are somewhat more realistic.

The results in table 1 show that the computed dihyperon masses are smaller than $2 \times \Lambda$ mass, implying that the dihyperon is stable against strong decays in the CCD model. The binding energy of the dihyperon varies between 160 MeV (for m_{GB} of 800 MeV) and 90 MeV (for m_{GB} of 1250 MeV). These values are larger than the result of S Ahmed *et al* [10] as well as Jaffe's prediction [1]. Similar values of dihyperon masses have been obtained by Nishikawa *et al* [14] (100–200 MeV of binding) and Pal and McGovern [15] (100 MeV of binding) in color dielectric model. However our calculation is better than these calculations in several respects. For example, Nishikawa *et al* do not include meson interactions. We also compute meson corrections and center of mass corrections more accurately.

To conclude, we have calculated the dihyperon mass using CCD model. Along with the color magnetic energy, we have also investigated the effect of the quark–meson coupling on the dihyperon mass. The correction due to the spurious motion of the center of mass is included in the calculation. The projection technique is used to project the good momentum states and these states are used in the computation of the dibaryon–meson form factors. It is found that the dihyperon is stable against the strong decays for the parameters of the CCD model considered in the calculations with the binding energy of about 100 MeV or more. The determination of the dihyperon width (due to the weak interaction), masses of other dibaryons and their strong decay widths (due to their decay into a pair of baryons) in the CCD model needs to be done. These calculations are in progress.

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