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There Might be Two Kinds of Dibaryon

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Abstract

A new quark potential model, the quark delocalization and color screening model, is used for a systematic search of dibaryon candidates in the u, d and s three flavor world. The color screening results from unquenched lattice gauge calculations and quark delocalization similar to electron delocalization in molecular physics are included. Flavor symmetry breaking and channel coupling effects are studied. The model is constrained not only by the baryon ground state property but also by the N-N scattering phase shifts. The deuteron and the zero energy di-nucleon resonance are reproduced qualitatively. The model predicts that there might be two kinds of dibaryon states. Possible high spin dibaryon resonances are emphasized.

Since the first calculation of Jaffe for the H-particle¹, there have been many of experimental and theoretical efforts on the dibaryon search. Up to now, there are no experimentally well established dibaryon states except the deuteron. Theoretically almost all QCD models, including lattice QCD, predict that there should be a dibaryon state. However none have arrived at the level of quantitative reliability. Either the model Hamiltonian is oversimplified or the model Hilbert space is rather restricted, or both. In many dibaryon calculations, the model parameters are constrained by single hadron properties only. Very few calculations take the experimental data of baryon-baryon scattering into account, but in these calculations usually a phenomenological meson exchange interaction is invoked. However, it is well known that the meson exchange model is not reliable in the short distance region, and the dibaryon properties are expected to be sensitive to that interaction.

To remedy these model deficiencies, we developed a model which we call the quark delocalization, color screening model (QDCSM)² The model Hamiltonian is the same as the usual quark confinement potential model, except the confinement interaction is modified to be either

$$V_{ij}^c = \begin{cases} -\vec{\lambda}_i \cdot \vec{\lambda}_j a r_{ij}^2 & \text{if } i, j \text{ occur in the same baryon orbit,} \\ -\vec{\lambda}_i \cdot \vec{\lambda}_j \frac{a}{\mu} (1 - e^{-\mu r_{ij}^2}) & \text{if } i, j \text{ occur in different baryon orbits;} \end{cases} \quad (1A)$$

or

$$V_{ij}^c = \begin{cases} -\vec{\lambda}_i \cdot \vec{\lambda}_j a r_{ij}^2 & \text{if } i, j \text{ occur in the same baryon orbit,} \\ -\vec{\lambda}_i \cdot \vec{\lambda}_j a r_{ij}^2 e^{-\mu r_{ij}^2} & \text{if } i, j \text{ occur in different baryon orbits.} \end{cases} \quad (1B)$$

For a single baryon, this model Hamiltonian is exactly the same as the usual one; for the dibaryon case, the confinement interaction between two quarks located in different color-singlet baryons is screened by $q - \bar{q}$ excitations as demonstrated in lattice QCD calculation^{18,3}. The model Hilbert space is the usual quark cluster model space

$$\Psi_\alpha(q^6) = \mathcal{A}[\psi_{B_1} \psi_{B_2}]_\alpha \quad (2)$$

$$\psi_{B_1}(q^3) = \chi(123) \eta_{\alpha_1}(123) \Pi_{i=1}^3 \psi_L(i) \quad (2a)$$

$$\psi_{B_2}(q^3) = \chi(456) \eta_{\alpha_2}(456) \Pi_{j=4}^6 \psi_R(j) \quad (2b)$$

Where $\mathcal{A}$ is the normalized antisymmetrization operator, $\alpha = (SIJ)$, $[\]_\alpha$ means the baryon isospin and spin are coupled into channel isospin-spin I, J . χ and η are the baryon color and spin-flavor wave functions(WF).

The only difference from the usual cluster model is that instead of the two center quark wavefunction,

$$\phi_L(\vec{r}) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{(\vec{r}+\vec{s}/2)^2}{2b^2}}, \quad \phi_R(\vec{r}) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{(\vec{r}-\vec{s}/2)^2}{2b^2}}$$

We introduce delocalized quark orbits,

$$\psi_L(\vec{r}_1) = N^{-\frac{1}{2}} [\phi_L(\vec{r}_1) + \epsilon(s) \phi_R(\vec{r}_1)] \quad (3a)$$

$$\psi_R(\vec{r}_2) = N^{-\frac{1}{2}} [\phi_R(\vec{r}_2) + \epsilon(s) \phi_L(\vec{r}_2)] \quad (3b)$$

Here, $\epsilon(s)$ is a parameter describing the delocalization due to the mutual interaction of two baryons and it is determined variationally by the q^6 dynamics for each $\vec{s}$, the distance between two baryon centers.

The model parameters, the u, d quark mass m , strange quark mass m_s , baryon size b , quark gluon coupling constant α_s , the strength of confinement a , are determined by an overall fit to the ground state masses of the octet and decuplet baryons. The fitted parameters and baryon masses(in MeV) are listed below:

$$m = 313 \text{ MeV}, m_s = 633.76 \text{ MeV}, b = 0.603 \text{ fm}, \alpha_s = 1.54, a = 25.13 \text{ MeV fm}^{-2}$$

	N	Δ	Λ	Σ	Ξ	Σ^*	Ξ^*	Ω
exp.	939	1232	1115	1193	1318	1385	1533	1672
theor.	939	1232	1118	1217	1359	1361	1504	1658

We first did a dynamical single channel N-N scattering calculation in which the color screening parameter μ is adjusted to give its best fit of the 1S_0 , 3S_1 , 1P_1 , and 1D_2 phase shifts and the fitted value is $\mu(A) = 1.0, \mu(B) = 0.4$. The preliminary results of $\Lambda - N$ and $\Sigma - N$ scattering are encouraging.

Then we did a multichannel coupling adiabatic calculation to obtain the lowest energy surface of all the possible states consisting of the octet and decuplet baryons. In order to show the effect of channel coupling and flavor symmetry breaking, the four sets of single channel, multichannel, flavor symmetry, flavor symmetry breaking results of interesting dibaryon candidates are listed in Table 1. In addition, to show the effect of color screening version, two sets of results corresponding to screening version (1A) and (1B) are also listed in Table 1. In addition to the results listed in Table 1, which correspond to the best fit screening parameters $\mu(A) = 1.0, \mu(B) = 0.4$, the results corresponding to $\mu(A) = 1.6$ and $\mu(B) = 0.46$ and 0.4 , are also calculated, to show the screening parameter dependence.

A relativistic potential model(LAMP)⁵ has been used to check the relativistic effect on the dibaryon state. The fractional parentage expansion method developed for the nonrelativistic quark cluster model has been extended to the Dirac quark cluster model. Only the one body and two body matrix elements have to be replaced by the relativistic ones:

$$H(i) = \vec{\alpha} \cdot \vec{p} + \beta(m + V) \quad (4a)$$

$$H(ij) = -g_s \vec{\alpha}_i \cdot \vec{\alpha}_j \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{4} G(\vec{r}_i, \vec{r}_j) \quad (4b)$$

Where $\vec{\alpha}, \beta$ are the Dirac 4x4 matrices,

$$m = \begin{cases} 0 & \text{u, d quark} \\ 0.3 \text{ GeV} & \text{s quark} \end{cases}$$

$$V(r) = V_0(r - r_0) \quad (\text{single baryon})$$

$$V_0 = 0.9 \text{ GeV/fm} \quad r_0 = 0.57 \text{ fm}$$

$$V_2(r) = V(\min|\vec{r} - \vec{R}_i|) \quad i = 1, 2 \quad (\text{dibaryon})$$

$$G(\vec{r}_i, \vec{r}_j) = A \exp(-\nu(\vec{r}_i - \vec{r}_j)^2)$$

g_s is the quark-gluon coupling constant, $\nu = \left(\frac{0.2 \text{ GeV}}{\hbar c}\right)^2 = 1.014 \text{ fm}^{-2}$, the product Ag_s is adjusted to fit the N- Δ mass difference.

It is worth to mention that the two radically different models, one a relativistic mean field approach with a truncated linear confinement, the other nonrelativistic

with a color screened quadratic confining pair interaction, yield almost the same results. This might be taken as an evidence of the qualitative reliability of our model prediction on the dibaryon states.

The quantitative prediction of QDCSM and LAMP on the energy of dibaryon states is still not reliable due to the simplified model Hamiltonian, the restricted Hilbert space and the adiabatic approximation etc. Qualitatively, that there might be two kinds of dibaryon is strongly shown by this systematic search. One kind is the loosely bound two baryon state, where the binding energy is small, $J \leq 1$, and the delocalization $\epsilon(s_0)$ is small also. A typical example is the deuteron. These states are very sensitive to the model details; they are either strong interaction stable or very broad. Even though the H-particle is strong interaction stable within our model, due to numerical uncertainty and above mentioned fact, we cannot claim the H-particle is a weak decaying particle.

Another kind is a tightly bound state, where the binding energy is large (≥ 100 MeV), $J \geq 2$, and the delocalization is large also. The mass is larger than the lowest two-body threshold and the state is therefore strong interaction unstable. However the mass is lower than or close to the favorable three body decay threshold. The two-body decay of these states is hindered due to the large angular momentum and so they might be narrow resonances. A typical example is the di- Δ (003) state. The quasi-stable property is not sensitive to model details unless a radically different model assumption is made. We recommend the $(\alpha = (003), (-3\frac{1}{2}2))$ as good candidates for observable dibaryon states⁴.

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² F. Wang et al., Phys. Rev. Lett. **68** (1992) 2901.

³ K.D. Born et al., Phys. Rev. **D40** (1989) 1653.

⁴ T. Goldman, et al., Phys. Rev. Lett. **59** (1987) 627; Phys. Rev. **C38**, (1989) 1889.

⁵ T. Goldman et al., Nucl. Phys. **A481**, (1988) 621.

TABLE 1: Dibaryon candidates (energy unit: MeV, s_0 : fm). scs-single channel flavor symmetry, ccs-multi-channel flavor symmetry, scb-single channel flavor symmetry breaking, ccb-multi-channel flavor symmetry breaking.

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Table 1

		(1B)						(1A)					
SIJ		M_α	V_α	B_α	ϵ	s_0	M_α	V_α	B_α	ϵ	s_0	Threshold	
001	scs	1869	-46	-9	0.2	1.3	1873	-42	-5	0.2	1.3	1878(NN)	
	ccs	1867	-48	-11	0.3	1.3	1873	-42	-5	0.2	1.3		
010	scs	1890	-20	12	0.2	1.4	1885	-18	7	0.1	1.6	1878(NN)	
	ccs	1888	-22	10	0.2	1.4	1885	-18	7	0.1	1.6		
003	scs	2074	-422	-390	1.0	1.2	2084	-413	-380	1.0	1.2	2464($\Delta\Delta$) 2158(NN $\pi\pi$)	
$-1\frac{1}{2}3$	scs	2225	-422	-390	1.0	1.2	2235	-413	-382	1.0	1.2	2617($\Delta\Sigma^*$)	
	ccs	2225	-422	-390	1.0	1.2	2235	-413	-382	1.0	1.2	2335($N\Lambda\pi\pi$)	
	scb	2285	-369	-332	1.0	1.1	2292	-361	-324	1.0	1.1		
	ccb	2285	-369	-332	1.0	1.1	2292	-361	-324	1.0	1.1		
$-1\frac{3}{2}0$	scs	2119	-41	-13	0.2	1.4	2123	-37	-9	0.2	1.4	2132($N\Sigma$)	
	ccs	2119	-41	-13	0.2	1.4	2123	-37	-9	0.2	1.4		
	scb	2126	-34	-6	0.2	1.4	2130	-30	-2	0.2	1.4		
	ccb	2126	-34	-6	0.2	1.4	2130	-30	-2	0.2	1.4		
-200	scs	2097	-244	-161	1.0	0.8	2097	-244	-161	0.9	0.8	2231($\Lambda\Lambda$)	
	ccs	1974	-364	-257	1.0	0.7	2012	-365	-220	1.0	0.6		
	scb	2282	-240	-104	1.0	0.6	2281	-241	-105	1.0	0.6		
	ccb	2176	-200	-55	1.0	0.6	2175	-202	-56	1.0	0.6		
-202	scs	2242	-272	-231	0.8	1.1	2249	-265	-223	0.7	1.1	2472($N\Xi^*$)	
	ccs	2150	-373	-323	1.0	1.0	2155	-368	-318	1.0	1.0	2397($N\Xi\pi$)	
	scb	2413	-221	-164	0.9	0.9	2429	-219	-148	1.0	0.8		
	ccb	2319	-231	-153	1.0	0.8	2320	-230	-152	1.0	0.8		
-213	scs	2372	-423	-393	1.0	1.2	2382	-413	-383	1.0	1.2	2765($\Delta\Xi^*$)	
	ccs	2372	-423	-393	1.0	1.2	2382	-413	-383	1.0	1.2	2690($\Delta\Xi\pi$)	
	scb	2496	-308	-273	1.0	1.1	2509	-302	-260	1.0	1.0	2511($\Lambda\Lambda\pi\pi$)	
	ccb	2493	-308	-272	1.0	1.1	2506	-302	-259	1.0	1.0		
-220	scs	2391	-20	5	0.2	1.4	2388	-18	2	0.1	1.6	2386($\Sigma\Sigma$)	
	ccs	2390	-21	4	0.2	1.4	2388	-18	2	0.1	1.6		
	scb	2382	-33	-4	0.2	1.3	2386	-29	0	0.2	1.3		
	ccb	2381	-34	-5	0.2	1.3	2385	-30	-1	0.2	1.3		
$-3\frac{3}{2}3$	scs	2510	-423	-394	1.0	1.2	2520	-413	-384	1.0	1.2	2904($\Delta\Omega$)	
	ccs	2510	-423	-394	1.0	1.2	2520	-413	-384	1.0	1.2	2788($\Lambda\Xi^*\pi$)	
	scb	2704	-254	-214	1.0	1.0	2717	-250	-201	1.0	0.9	2714($\Lambda\Xi\pi\pi$)	
	ccb	2691	-255	-213	1.0	1.0	2705	-250	-200	1.0	0.9		
$-3\frac{3}{2}1$	scs	2493	-46	-18	0.2	1.3	2497	-42	-14	0.2	1.3	2511($\Sigma\Xi$)	
	ccs	2491	-48	-20	0.3	1.3	2497	-42	-14	0.2	1.3		
	scb	2498	-60	-13	0.4	1.0	2501	-57	-10	0.3	1.0		
	ccb	2497	-61	-14	0.4	1.0	2500	-58	-11	0.4	1.0		
$-3\frac{1}{2}2$	scs	2339	-321	-272	1.0	1.0	2344	-316	-268	1.0	1.0	2611($N\Omega$)	
	ccs	2287	-373	-324	1.0	1.0	2292	-368	-319	1.0	1.0	2574($\Lambda\Xi\pi$)	
	scb	2510	-313	-193	1.0	0.6	2508	-304	-194	1.0	0.6		
	ccb	2506	-240	-106	1.0	0.6	2504	-242	-107	1.0	0.6		
$-3\frac{1}{2}1$	scs	2339	-321	-272	1.0	1.0	2344	-316	-268	1.0	1.0	2434($\Lambda\Xi$)	
	ccs	2337	-156	-97	1.0	0.9	2340	-154	-94	1.0	0.9		
	scb	2474	-167	-38	1.0	0.6	2437	-131	3	1.0	0.6		
	ccb	2422	-146	-11	1.0	0.6	2421	-147	-13	1.0	0.6		
-400	scs	2617	-41	-19	0.2	1.4	2622	-37	-15	0.2	1.4	2636($\Xi\Xi$)	
	ccs	2617	-41	-19	0.2	1.4	2622	-37	-15	0.2	1.4		
	scb	2628	-45	-8	0.3	1.1	2630	-43	-6	0.2	1.1		
	ccb	2627	-46	-9	0.3	1.1	2630	-43	-6	0.2	1.1		
-600	scs	3251	-112	-94	0.3	1.4	3260	-102	-84	0.3	1.4	3345($\Omega\Omega$)	
	scb	3376	-65	32	1.0	0.6	3375	-67	30	1.0	0.6		