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A closer look to the H dibaryon

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The H dibaryon was examined within a chiral constituent quark model. The parameters were fitted to describe the strangeness –1 and –2 cross sections and therefore predictive power is expected. A detailed analysis of the contributions of the interacting potential as well as the number of coupled channels considered is performed. We obtain a slightly bound H dibaryon, with $B_H =$ 7 MeV, compatible with the constraint given by the Nagara event, that falls within a plausible extrapolation of recent lattice QCD results.

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The H dibaryon was suggested more than 30 years ago by Jaffe [1] in the context of the MIT bag model as a stable, flavor singlet state with strangeness -2 and quantum numbers $J^P = 0^+$ at 2150 MeV, therefore 81 MeV below the $\Lambda\Lambda$ threshold. It was considered to be a compact state where all six quarks are squeezed in a small region. Since multiquarks in nature have not been found so far, the H dibaryon is interesting as it is a promising candidate. The H dibaryon can be approached through the baryon–baryon scattering considering all possible strangeness -2 two–body states coupled to $J^P = 0^+$: $\Lambda\Lambda$, NΞ and $\Sigma\Sigma$.

On the experimental side, many searches have been performed by several methods, but no conclusive evidence has already been found. It is not easy to decide whether the enhancements of the $\Lambda\Lambda$ invariant mass mean a resonance or whether they can be explained through the $\Lambda\Lambda$ final state interactions instead. As no information can be extracted from direct searches, one needs to have a look at double hypernuclei. They provide the only constraint known so far to the mass of the dibaryon. The binding energy of H needs to be smaller than the binding energy $B_{\Lambda\Lambda}$ of the double hypernucleus. Therefore one has to look at the double hypernuclear events reported to date. The most stringent constraint is given by the so–called Nagara event [2], giving $B_H < 7.13$ MeV. Therefore if such an object exists, it should be slightly bound.

From the theoretical side, many approaches have been done: bag models, skyrmions, non-relativistic quark models, QCD sum rules, etc.. [3] but no general trend has been found. This situation is in clear contrast with the agreement that all these frameworks exhibit when studying spectroscopy, and shows the importance of this problem to discriminate among the different approaches.

The basic mechanism that is expected to give large attraction in the original work [1] is the chromomagnetic interaction (CMI), which is proportional to $\sigma_i \cdot \sigma_j \lambda_i \cdot \lambda_j$, being σ_i and λ_i the Pauli and the color matrices of the ith quark. The value given by the CMI operator is smaller for a six–quark configuration than for a two–baryon one. However, quark model's approach to the problem assumes a two–baryon configuration, studying then the baryon–baryon interaction by using quark degrees of freedom and finally searching for a bound state.

There has been a steady progress in the lattice calculations during the last years. Two collaborations (NPLQCD [4] and HALQCD [5]) reported to have found a bound H dibaryon. Unfortunately, these results are obtained by using nonphysical pion masses: 390 MeV for NPLQCD and 837 MeV for HALQCD collaborations. To obtain a prediction for B_H at a physical value of m_π two different extrapolations have been done [6]: quadratic, that leads to a bound dibaryon ($B_H = 7.4 \pm 2.1 \pm 5.8$ MeV) and linear, that gives a dibaryon at threshold ($B_H = -0.2 \pm 3.3 \pm 7.3$ MeV). Due to uncertainties, it is not possible to discriminate between bound or unbound.

Our study of the H dibaryon is based on a chiral constituent quark model. It is a nonrelativistic potential model that reproduces the basic properties of QCD: asymptotic freedom, confinement and chiral symmetry. Due to spontaneous breaking of chiral symmetry, current quarks acquire mass, becoming constituent quarks, whereas Goldstone bosons become massive. One has two different scales, associated to confinement and chiral symmetry breaking. Quarks, gluons and Goldstone bosons interact in the region between both. The quark–quark potential has a confinement piece, a perturbative one–gluon exchange (OGE) and a chiral potential. The model was born to be applied to the nonstrange SU(2)$\times$SU(2) sector, and successfully described interaction and baryon spectrum, NN phase shifts and deuteron properties [7]. The extension to SU(3) symmetry can be

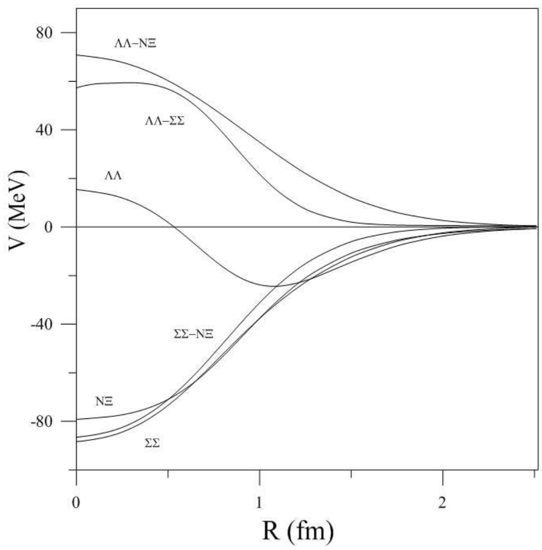

Figure 1: Interacting potentials contributing to the H dibaryon

implemented in two different ways, being the main difference between both the presence or absence of an scalar–octet exchange. The choice we will take hereforth contains, besides the confinement and perturbative pieces, a pseudoscalar octet (PSE), a scalar singlet (σ_0) and also a scalar octet (SCE) pieces. It has succeeded describing hypertriton [8] and strangeness –1 and –2 elastic and inelastic cross sections [9]. It reads:

$$V_{qq}(\vec{r}) = V_{\mathrm{CON}}(\vec{r}) + V_{\mathrm{OGE}}(\vec{r}) + V_{\sigma_0}(\vec{r}) + V_{\mathrm{SCE}}(\vec{r}) + V_{\mathrm{PSE}}(\vec{r})\,. \tag{1}$$

Once the quark–quark potential is known, the baryon–baryon interactions are built through a Born–Oppenheimer approach. Next, one has to solve the two–body coupled–channel problem. We start by considering a physical system made of two–baryons with I, J and P. In general, there is a coupling to any other two–baryon system having the same quantum numbers.

For SU(3) exact, the flavor singlet state can be written in the particle basis, as

$$|H\rangle = \sqrt{\frac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\frac{4}{8}}|N\Xi\rangle - \sqrt{\frac{3}{8}}|\Sigma\Sigma\rangle\,. \tag{2}$$

We have found that ΛΛ is weakly attractive with a repulsive core. In contrast, NΞ and ΣΣ present deeper attraction, as can be seen in Figure 1. The one–channel binding energies of these diagonal interactions, with respect to their own thresholds are 0.1 MeV for both NΞ and ΣΣ. ΛΛ is not bound. The magnitude of the three transition potentials $\Lambda\Lambda - N\Xi$, $\Lambda\Lambda - \Sigma\Sigma$ and $\mathrm{N}\Xi - \Sigma\Sigma$ is comparable to the diagonal potentials, showing that the effect of channel coupling is strong. To get more insight on the structure of the H dibaryon, we have computed the binding energy in the one–, two–, and the complete three-channel approaches for different pieces in the potential, as shown in Table 1. First we realize that OGE is repulsive in our model [10], opposite to the behaviour found in the early works. The PSE contribution shares this repulsive feature. The scalar singlet σ_0 exchange is the only attractive piece in the three approaches. Note that in a model containing only σ_0 the $\Lambda\Lambda - N\Xi$

Table 1: Character of the strangeness –2 two–baryon interaction in the one–, two– and three–channel approximations, for different quark–quark interactions. R indicates repulsion, WA weak attraction, $A(N)$ indicates attraction, being N the binding energy in MeV. PSE stands for the pseudoscalar exchange, OGE for gluon, SCE for the scalar octet and σ_0 for the scalar singlet as indicated in Eq. (1)

	$B_{\{\Lambda\Lambda\}}$	$B_{\{\Lambda\Lambda,N\Xi\}}$	$B_{\{\Lambda\Lambda,N\Xi,\Sigma\Sigma\}}$
OGE	R	R	R
PSE	R	R	R
σ_0	A(5.4)	A(5.4)	A(8.3)
SCE	WA	WA	R
OGE + PSE	R	R	R
σ_0 + PSE	A(0.1)	A(0.1)	A(0.4)
OGE + σ_0	A(0.1)	A(0.1)	A(0.6)
OGE + PSE + σ_0	WA	WA	WA
OGE + PSE + σ_0 + SCE	WA	A(1.6)	A(7.0)

transition would never be possible. This transition is mainly driven by the κ exchange, that belongs to the scalar octet exchange. Without such a transition one would get a zero probability associated to the NΞ state and so the wave function would be completely different to the flavor singlet (2). Therefore, although a binding energy of a few MeV is guaranteed by the σ_0 contribution, one needs to include more physics. The contribution given by the scalar octet (SCE) turns out to be crucial to understand the H dibaryon in our model. Its character ranges between a weak attraction for the one– and two–channel approximations and repulsion for the three–channel calculation. However, when adding the scalar piece to the OGE + PSE + σ_0 contribution, the weak attraction (not enough to form a bound state) turns into a binding energy of 7 MeV. Although weak by itself, the SCE contribution is the responsible not only for the binding energy obtained in our model but also for a correct description of the ΛΛ, NΞ and ΣΣ probabilities. This is possible because the κ and K exchanges are the main pieces that connect ΛΛ to the more attractive NΞ and ΣΣ channels.

As we have just seen, the binding of the H dibaryon depends most on the σ_0 and κ exchange potentials. Therefore we have computed the variation of the binding energy as a function of the coupling constant of the σ_0, and the masses of the σ_0 and κ mesons, as can be found in Figure 2. As $g^2_{\sigma_0}/4\pi$ increases, the dibaryon becomes more bound. The dependence with m_κ and m_{σ_0} is opposite: as the masses get larger, the dibaryon is less and less bound. These variations let us arrive to a couple of conclusions: first, a loosely bound dibaryon is allowed in our model, and second, the H dibaryon is bound in our model for any reasonable choice of the parameters.

Flavor symmetry breaking (FSB) is expected to be large as there are two strange quarks in this system. Our model assumes broken SU(3) and several sources of symmetry breaking take part. Not only a different mass is given to the strange quark, but also a different oscillator parameter ($b_s \neq b$) is assigned in the orbital wave function. Therefore the number of allowed interacting diagrams is dramatically reduced because an exchange of a strange and a light quark is not allowed as they are distinguishable particles. When trying to restore SU(3) symmetry, by removing all possible sources

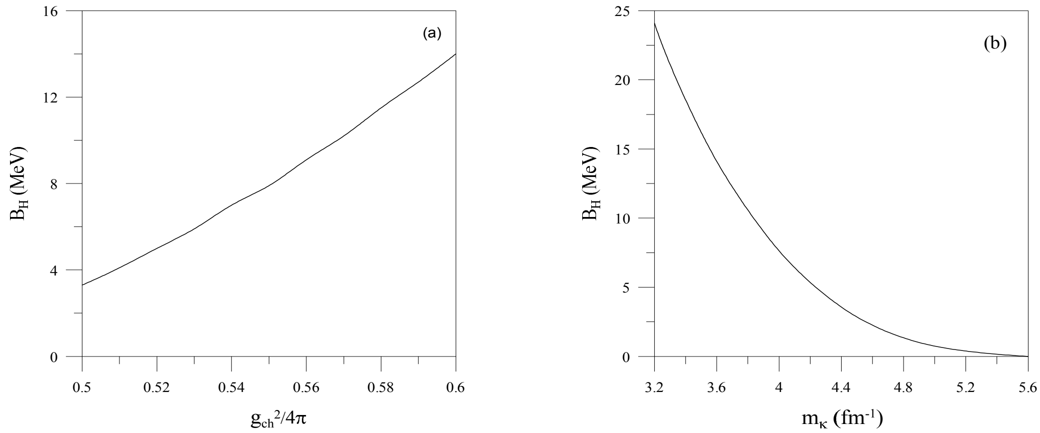

Figure 2: Dependence of B_H on the masses of (a) the coupling constant and (b) m_κ.

of FSB in our model, we get $B_H = 10.5$ MeV, around 50% larger. We conclude that FSB lowers the attraction, a feature that is shared by other quark–model studies of the H dibaryon [11, 12, 13].

Although the original work suggested a compact six–quark configuration, different calculations within the quark model framework found that a dibaryon containing only the $(0s)^6$ configuration would not bind [14, 15]. It is thus necessary to consider less compact configurations to benefit from the medium–range attraction associated to the σ exchange.

The procedure to obtain the physical probabilities of different channels in the Resonating Group Method treatment usually starts by postulating the SU(3) flavor singlet wave function of Eq. (2), performing afterwards a perturbative variational calculation. This is not the case of our work, since the coefficients of the baryon–baryon components of the flavor wave function are obtained as an output of the calculation, without making further assumptions. The probabilities we got are $P_{\Lambda\Lambda} = 0.177$, $P_{N\Xi} = 0.446$ and $P_{\Sigma\Sigma} = 0.377$. They are quantitatively similar to those of the flavor singlet, from what we can infer that in our model the baryon–baryon wave function is at first approximation SU(3) symmetric, being the difference between both due to the flavor symmetry breaking effects.

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