Strangeness $-2$ two-baryon systems

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Abstract

We derive strangeness $-2$ baryon-baryon interactions from a chiral constituent quark model including the full set of scalar mesons. The model has been tuned in the strangeness 0 and $-1$ two-baryon systems, providing parameter free predictions for the strangeness $-2$ case. We calculate elastic and inelastic $N\Xi$ and $\Lambda\Lambda$ cross sections which are consistent with the existing experimental data. We also calculate the two-body scattering lengths for the different spin-isospin channels.

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I. INTRODUCTION

The knowledge of the strangeness $S = -2$ two-baryon interactions has become an important issue for theoretical and experimental studies of the strangeness nuclear physics. Moreover, this is an important piece of a more fundamental problem, the description of the interaction of the different members of the baryon octet in a unified way. The $\Xi N - \Lambda \Lambda$ interaction accounts for the existence of doubly strange hypernuclei, which is a gateway to strange hadronic matter. Strangeness $-2$ baryon-baryon interactions also account for a possible six-quark $H$-dibaryon, which has yet to be experimentally observed. Its knowledge is naturally invaluable for the quantitative predictions for various aspects of neutron star matter.

There has been a steady progress towards the $S = -2$ baryon-baryon interaction. The $\Lambda N$ interaction is pretty much understood based on the experimental data of $\Lambda$ hypernuclei. There is also some progress made on the $\Sigma N$ interaction. However, the experimental knowledge on the $\Xi N$ and hyperon-hyperon ($YY$) interactions is quite poor. The only information available came from doubly strange hypernuclei, suggesting that the $^1S_0 \Lambda \Lambda$ interaction should be moderately attractive. An upper limit of $B_{\Lambda \Lambda} = 7.25 \pm 0.19$ MeV has been deduced for an hypothetical $H$-dibaryon (a lower limit of $2223.7$ MeV/$c^2$ for its mass) from the so-called Nagara event [1] at a 90% confidence level. The KEK-E176/E373 hybrid emulsion experiments observed other events corresponding to double $-\Lambda$ hypernuclei. Among them, the Demachi-Yanagi [2, 3], identified as $^{10}_{\Lambda \Lambda}$Be drove a value of $B_{\Lambda \Lambda} = 11.90 \pm 0.13$ [4]. A new observed double-$\Lambda$ event has been recently reported by the KEK-E373 experiment, the Hida event [3], although with uncertainties on its nature it has been interpreted as an observation of the ground state of the $^{11}_{\Lambda \Lambda}$Be [4]. Very recently, doubly strange baryon-baryon scattering data at low energies were deduced for the first time, obtaining some experimental data and upper limits for different elastic and inelastic cross sections: $\Xi^{-} p \rightarrow \Xi^{-} p$ and $\Xi^{-} p \rightarrow \Lambda \Lambda$ [5]. Recent results of the KEK-PS E522 experiment indicates the possibility of a $H$-dibaryon as a resonance state with a mass range between the $\Lambda \Lambda$ and $N \Xi$ thresholds [6].

In the planned experiments at J-PARC [7], dozens of emulsions events for double $-\Lambda$ hypernuclei will be produced. The $(K^{-}, K^{+})$ reaction is one of the most promising ways of studying doubly strange systems. $\Lambda \Lambda$ hypernuclei can be produced through the reaction $K^{-} p \rightarrow K^{+} \Xi^{-}$ followed by $\Xi^{-} p \rightarrow \Lambda \Lambda$. It is therefore compulsory having theoretical predictions concerning the $\Xi N - \Lambda \Lambda$ coupling [8] to guide the experimental way and, in a symbiotic manner, to use the new experimental data as a feedback of our theoretical knowledge. Such a process may shed light on our understanding of the nature of $SU(3)$ symmetry breaking in the baryon-baryon interaction. Knowledge of the strangeness $-2$ sector is therefore a challenge for understanding the baryon-baryon interaction in a unified way. The chiral constituent quark model has been very successful in the simultaneous description of the baryon-baryon interaction and the baryon spectrum as well as in the study of the two- and three-baryon bound-state problem for the nonstrange sector [9]. A generalization to the strange sector has been applied to study the meson and baryon spectra [10], giving a nice description of the hyperon-nucleon elastic and inelastic cross sections, and valuable predictions for the strangeness $-1$ three-baryon systems: $\Lambda NN - \Sigma NN$ [11].

In this work, we will apply the same model to derive the strangeness $-2$ baryon-baryon interactions: $\Lambda \Lambda$, $\Lambda \Sigma$, $\Sigma \Sigma$ and $N \Xi$. We will use these two-body interactions to calculate two-body elastic and inelastic scattering cross sections and we will compare to experimental data and other theoretical models. We will also calculate the two-body scattering lengths of
the different spin-isospin channels to compare with other theoretical models. The structure of the paper is the following. In the next section we will resume the basic aspects of the two-body interactions and we will present the integral equations for the different two-body systems. In section III we present our results compared to other models and the available experimental data. Finally, in section IV we summarize our main conclusions.

II. FORMALISM

A. The strangeness $-2$ baryon-baryon potential

The baryon-baryon interactions involved in the study of the coupled $\Lambda \Lambda - N \Xi - \Lambda \Sigma - \Sigma \Sigma$ system are obtained from the chiral constituent quark model [9]. In this model baryons are described as clusters of three interacting massive (constituent) quarks, the mass coming from the spontaneous breaking of chiral symmetry. The first ingredient of the quark-quark interaction is a confining potential ($CON$). Perturbative aspects of QCD are taken into account by means of a one-gluon potential ($OGE$). Spontaneous breaking of chiral symmetry gives rise to boson exchanges between quarks. In particular, the re appear pseudoscalar boson exchanges and their corresponding scalar partners [11]. Thus, the quark-quark interaction will read:

$$V_{qq}(\vec{r}_{ij}) = V_{CON}(\vec{r}_{ij}) + V_{OGE}(\vec{r}_{ij}) + V_{\chi}(\vec{r}_{ij}) + V_{S}(\vec{r}_{ij}),$$

where the $i$ and $j$ indices are associated with $i$ and $j$ quarks respectively, and $\vec{r}_{ij}$ stands for the interquark distance. $V_\chi$ denotes the pseudoscalar meson-exchange interaction and $V_S$ stands for the scalar meson-exchange potential described in Ref. [11]. Explicit expressions of all the interacting potentials and a more detailed discussion of the model can be found in Refs. [10, 11]. In order to derive the local $B_1B_2 \rightarrow B_3B_4$ potentials from the basic $qq$ interaction defined above we use a Born-Oppenheimer approximation. Explicitly, the potential is calculated as follows,

$$V_{B_1B_2(LST)\rightarrow B_3B_4(U'S'T)}(R) = \xi^{U'S'T}_{LST}(R) - \xi^{U'S'T}_{LST}(\infty),$$

where

$$\xi^{U'S'T}_{LST}(R) = \frac{\langle \Psi^{L'S'T}_{B_3B_4}(\vec{R}) | \sum_{i<j=1}^6 V_{qq}(\vec{r}_{ij}) | \Psi^{LST}_{B_1B_2}(\vec{R}) \rangle}{\sqrt{\langle \Psi^{U'S'T}_{B_3B_4}(\vec{R}) | \Psi^{L'S'T}_{B_3B_4}(\vec{R}) \rangle \langle \Psi^{LST}_{B_1B_2}(\vec{R}) | \Psi^{LST}_{B_1B_2}(\vec{R}) \rangle}}.$$  \(3\)

In the last expression the quark coordinates are integrated out keeping $R$ fixed, the resulting interaction being a function of the $B_i - B_j$ relative distance. The wave function $\Psi^{L'S'T}_{B_iB_j}(\vec{R})$ for the two-baryon system is discussed in detail in Ref. [9].

B. Integral equations for the two-body systems

If we consider the system of two baryons $B_1$ and $B_2$ with strangeness $-2$, $N \Xi$ and $Y_1Y_2$ ($Y_i = \Sigma, \Lambda$), in a relative $S$–state interacting through a potential $V$ that contains a tensor force, then there is a coupling to the $B_1B_2 D$–wave so that the Lippmann-Schwinger equation for the spin singlet channels of Table I is of the form
in the ΛΛ channel. Thus, in that case the cross section for isospin $i$ is

$$\sigma_i = \frac{2\mu_i}{k_i^2 - p^2 + i\epsilon} t_{\gamma-\beta;ji}(p',p'';W),$$  \hspace{1cm} (4)$$

where $t$ is the two-body amplitude, $j$, $i$, and $W$ are the total angular momentum, isospin and invariant energy of the system, and, for example, for $i = 0$ the subscripts $\alpha$, $\beta$, and $\gamma$ take the values $\Lambda\Lambda$, $N\Xi$ and $\Sigma\Sigma$, and similarly for the $i = 1$ and $i = 2$ channels shown in Table I.

For the spin triplet channels of Table I the Lippmann-Schwinger equation is of the form,

$$t_{\alpha-\beta;ji}(p,p'';W) = V_{\alpha-\beta;ji}(p,p'') + \sum_{\gamma} \int_0^\infty p'' dp' V_{\alpha-\gamma;ji}(p,p') \frac{2\mu_\gamma}{k_\gamma^2 - p'^2 + i\epsilon} t_{\gamma-\beta;ji}(p',p'';W),$$  \hspace{1cm} (5)$$

with $\mu_\gamma$ the reduced mass of the system and the on-shell momenta $k_\gamma$ are defined as

$$W = \sqrt{m_{1\gamma}^2 + k_\gamma^2} + \sqrt{m_{2\gamma}^2 + k_\gamma^2},$$  \hspace{1cm} (6)$$

where $m_1$ and $m_2$ are the masses of the particles of channel $\gamma$.

C. Scattering cross sections

We now turn to the available low-energy data on the $N\Xi$ scattering. There is only a small amount of data corresponding to the total cross sections for $\Xi^-p \rightarrow \Xi^-p$, $\Xi^-p \rightarrow \Xi^0n$, and $\Xi^-p \rightarrow \Lambda\Lambda$ reactions.

In the case of processes of the type $N\Xi \rightarrow N\Xi$ the amplitudes obtained from Eqs. (4) and (5) are related to the cross section for a given isospin state through,

$$\sigma^i = \pi^3 \mu_{N\Xi}^2 \left( 3 |t_{N\Xi^{-}\rightarrow N\Xi;10}^{00}|^2 + |t_{N\Xi^{-}\rightarrow N\Xi;00}^{00}|^2 \right).$$  \hspace{1cm} (7)$$

From the isospin cross sections the physical channels are determined through,

$$\sigma_{\Xi^-p \rightarrow \Xi^-p} = \frac{1}{4} \sigma_{i=1} + \frac{1}{4} \sigma_{i=0} + \frac{1}{2} \sqrt{\sigma_{i=0} \sigma_{i=1}},$$  \hspace{1cm} (8)$$

$$\sigma_{\Xi^-p \rightarrow \Xi^0n} = \frac{1}{4} \sigma_{i=1} + \frac{1}{4} \sigma_{i=0} - \frac{1}{2} \sqrt{\sigma_{i=0} \sigma_{i=1}}.$$

In the case of the process $N\Xi \rightarrow \Lambda\Lambda$ it is necessary to include also the transition with $\ell = 2$ in the $\Lambda\Lambda$ channel. Thus, in that case the cross section for isospin $i = 0$ is

$$\sigma^0 = \pi^3 \mu_{N\Xi} \mu_{\Lambda\Lambda} \left( |t_{\Lambda\Lambda^{-}\rightarrow \Lambda\Lambda;00}^{00}|^2 + 3 |t_{\Lambda\Lambda^{-}\rightarrow \Lambda\Lambda;10}^{00}|^2 + 3 |t_{\Lambda\Lambda^{-}\rightarrow \Lambda\Lambda;10}^{02}|^2 \right),$$  \hspace{1cm} (9)$$

and the cross section for the physical channel is

$$\sigma_{\Xi^-p \rightarrow \Lambda\Lambda} = \frac{1}{2} \sigma^0.$$  \hspace{1cm} (10)$$

Finally, for the elastic $\Lambda\Lambda \rightarrow \Lambda\Lambda$ process we have

$$\sigma_{\Lambda\Lambda \rightarrow \Lambda\Lambda} = 4\pi^3 \mu_{\Lambda\Lambda}^2 |t_{\Lambda\Lambda^{-}\rightarrow \Lambda\Lambda;00}^{00}|^2.$$  \hspace{1cm} (11)
III. RESULTS

Our results for the scattering cross sections are depicted by the solid lines in Figs. 1, 2, 3 and 4, compared to the available experimental data. The scattering lengths of the different spin-isospin channels are given in Table II compared to other theoretical models when available.

We show in Fig. 1 the $\Xi^{-}p$ elastic cross section compared to the in-medium experimental $\Xi^{-}p$ cross section around $p_{\text{lab}} = 550$ MeV/c, where $\sigma_{\Xi^{-}p} = 30 \pm 6.7 \pm 3.0$ mb [12]. Another analysis using the eikonal approximation gives $\sigma_{\Xi^{-}p} = 20.9 \pm 4.5 \pm 2.5$ mb [13]. A more recent experimental analysis [5] for the low energy $\Xi^{-}p$ elastic and $\Xi^{-}p \rightarrow \Lambda\Lambda$ total cross sections in the range 0.2 GeV/c to 0.8 GeV/c shows that the former is less than 24 mb at 90% confidence level and the latter of the order of several mb, respectively. In Fig. 2 we present the inelastic $\Xi^{-}p \rightarrow \Lambda\Lambda$ cross section. It has been recently estimated at a laboratory momentum of $p_{\text{lab}} = 500$ MeV/c, see Ref. [5], assuming a quasifree scattering process for the reaction $^{12}\text{C}(\Xi^{-}, \Lambda\Lambda)X$ obtaining a total cross section $\sigma(\Xi^{-}p \rightarrow \Lambda\Lambda) = 4.3^{+6.3}_{-2.7}$ mb. The upper limit of the cross section was derived as 12 mb at 90% confidence level. Fig. 3 shows the total inelastic cross section $\Xi^{-}p \rightarrow \Xi^{0}n$. Combining the results of Refs. [5] and [14], one obtains $\sigma(\Xi^{-}p \rightarrow \Xi^{0}n) \sim 10$ mb. A recent measurement of a quasifree $p(K^{-}, K^{+})\Xi^{-}$ reaction in emulsion plates yielded $12.7^{+3.5}_{-3.1}$ mb for the total inelastic cross section in the momentum range $0.4-0.6$ GeV/c [15], consistent with the results of Ref. [14]. The experimental results for $\Xi^{-}p$ inelastic scattering of Refs. [14, 15] involve both $\Xi^{-}p \rightarrow \Lambda\Lambda$ and $\Xi^{-}p \rightarrow \Xi^{0}n$ [5], what combined with the value for $\Xi^{-}p \rightarrow \Lambda\Lambda$ of Ref. [5] allows to obtain an estimate of the inelastic cross section $\Xi^{-}p \rightarrow \Xi^{0}n$. Finally in Fig. 4 we present our prediction for the $\Lambda\Lambda$ scattering cross section. In this last case there are no experimental data.

As can be seen our results agree with the experimental data for the elastic and inelastic $\Xi N$ cross sections. The small bumps in the cross sections correspond to the opening of inelastic channels. As explained above, the interacting model is taken for grant from Ref. [11], where three body systems with strangeness $-1$ were studied, involving therefore two-body subsystems with strangeness $0$ and $-1$. The agreement with the experimental data gives support to the dynamical model used and make our predictions valuable for forthcoming experiments. We would like to emphasize the agreement of our results with the $\Xi^{-}p \rightarrow \Lambda\Lambda$ conversion cross section. This reaction is of particular importance in assessing the stability of $\Xi^{-}$ quasi-particle states in nuclei. Our results are close to the estimations of the Nijmegen-D model [20]. Ref. [16] predicts $\sigma(\Xi^{-}p \rightarrow \Xi^{0}n) \sim 15$ mb at $p_{\text{lab}} = 0.5$ GeV/c. Ref. [14] reported 14 mb for the inelastic scattering involving both $\Xi^{-}p \rightarrow \Lambda\Lambda$ and $\Xi^{-}p \rightarrow \Xi^{0}n$. We found a smaller value of approximately 6 mb for both inelastic channels, in close agreement to experiment. In the case of the elastic $\Lambda\Lambda$ cross section there are no experimental data. Our predictions are rather similar to Refs. [16, 17]. We definitely need more experimental data with high statistics. This will help us in discriminating among the different dynamical models. A theoretical evaluation of the in-medium cross sections would also be necessary.

The scattering lengths for the different spin-isospin channels are given in Table II. These parameters are complex for the $N\Xi$ $(i, j) = (0, 0)$ since the inelastic $\Lambda\Lambda$ channel is open, for the $\Lambda\Sigma$ isospin 1 channel due to the opening of the $N\Xi$ channel, and for the $\Sigma\Sigma$ $i = 0$ and 1 since the $\Lambda\Lambda$ and $N\Xi$ channels are open in the first case, and the $N\Xi$ and $\Lambda\Sigma$ are open in the second (see Table I). There is no direct comparison between our results and those of Ref. [16]. Although both are quark-model based results, Ref. [16] used an old-fashioned quark-model interacting potential. For example, they use a huge strong coupling
constant, $\alpha_S = 1.9759$, and they consider the contribution of vector mesons what could give rise to double counting problems [21]. As explicitly written in Ref. [16], the parameters are effective in their approach and has very little to do with QCD. As mentioned above, since the observation of the Nagara event [1] it is generally accepted that the $\Lambda\Lambda$ interaction is only moderately attractive. Our result for the $^1S_0$ $\Lambda\Lambda$ scattering length is compatible with such event. A rough estimate of $B_{AA}(B_{AA} \approx (\hbar c)^2/2\mu_{AA}a_{^1S_0}^{AA})$ drives a value of 5.41 MeV, below the upper limit extracted from the Nagara event, $B_{AA} = 7.25 \pm 0.19$ MeV. Moreover, although from the $\Lambda\Lambda$ scattering length alone one cannot draw any conclusion on the magnitude of the two-$\Lambda$ separation energy, recent estimates [22] have reproduced the two-\Lambda separation energy, defined as $\Delta B_{AA} = B_{AA}(^6\Lambda\Lambda\text{He}) - 2B_{\Lambda}(^5\Lambda\text{He})$, with scattering lengths of $−1.32$ fm. The only reliable way to determine the two-$\Lambda$ separation energy in our model would be a concrete calculation of doubly-strange hypernuclei. This has not been done so far, and it is not clear that such calculation might help to further constrain the potential model.

IV. SUMMARY AND OUTLOOK

In this letter we have presented the first results for the doubly strange $N\Xi$ and $Y_iY_j$ interactions ($Y_i = \Sigma, \Lambda$) obtained with a constituent quark model approach designed to study the non-strange hadron phenomenology. The interaction incorporates long-ranged meson-exchange contributions and the short-range dynamics generated by the one-gluon exchange and quark antisymmetry contributions.

We showed that the CCQM predictions are consistent with the recently obtained doubly strange elastic and inelastic scattering cross sections. In particular, our results are compatible with the $\Xi^-p \rightarrow \Lambda\Lambda$ conversion cross section, important in assessing the stability of $\Xi^-$ quasi-particle states in nuclei. Furthermore a moderately attractive $\Lambda\Lambda$ interaction arises. The presently available scattering data are, however, not sufficient to draw definitive conclusions about the model, but forthcoming experimental data of the observables reported will help in testing different theoretical model predictions.

It is expected that in the coming years better-quality data on the fundamental $N\Xi$ and $YY$ interactions as well as much information about the physics of hypernuclei will become available at the new facilities J-PARC (Tokai, Japan) and FAIR (Darmstadt, Germany). The CCQM developed here can then be used to analyze these upcoming data in a model-independent way.

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TABLE I: Interacting channels on the spin($j$)-isospin($i$) basis for the $S - D$ partial waves.

| $j$   | $i = 0$     | $i = 1$     | $i = 2$     |
|-------|-------------|-------------|-------------|
| $j = 0$ | $\Lambda \Lambda - N \Xi - \Sigma \Sigma$ | $N \Xi - \Lambda \Sigma$ | $\Sigma \Sigma$ |
| $j = 1$ | $N \Xi$     | $N \Xi - \Lambda \Sigma - \Sigma \Sigma$ | $-$ |

TABLE II: Two-body singlet and triplet scattering lengths, in fm, for different models as compared to our results. The results between squared brackets indicate the lower and upper limit for different parametrizations used in that reference.

| Model       | Ref. [18]   | Ref. [19]   | Ref. [17]   | Ref. [16]   | Ours       |
|-------------|-------------|-------------|-------------|-------------|------------|
| $a_{1S_0}^{\Lambda \Lambda}$ | $[-0.27, -0.35]$ | $[-1.555, -3.804]$ | $[-1.52, -1.67]$ | $-0.821$ | $-2.54$ |
| $a_{1S_0}^{\Xi S_1}$ | $[0.40, 0.46]$ | $[0.144, 0.491]$ | $[0.13, 0.21]$ | $0.324$ | $-3.32$ |
| $a_{1S_0}^{\Sigma + \Sigma +}$ | $[-0.030, 0.050]$ | $-$ | $[0.0, 0.03]$ | $-0.207$ | $18.69$ |
| $a_{1S_0}^{\Sigma \Sigma (I=0)}$ | $[6.98, 10.32]$ | $-$ | $[-6.23, -9.27]$ | $-85.3$ | $0.523$ |
| $a_{1S_0}^{\Xi N (I=0)}$ | $-$ | $-$ | $-$ | $-$ | $-1.20 + i 0.75$ |
| $a_{3S_1}^{\Xi S_1}$ | $-$ | $[-1.672, 122.5]$ | $-$ | $-$ | $0.28$ |
| $a_{1S_0}^{\Lambda \Sigma}$ | $-$ | $-$ | $-$ | $-$ | $0.908 + i 1.319$ |
| $a_{1S_0}^{\Sigma \Sigma (I=1)}$ | $-$ | $-$ | $-$ | $-$ | $-3.116 + i 0.393$ |
| $a_{1S_0}^{\Sigma \Xi (I=0)}$ | $-$ | $-$ | $-$ | $-$ | $-1.347 + i 1.801$ |
| $a_{1S_0}^{\Sigma \Xi (I=0)}$ | $-$ | $-$ | $-$ | $-$ | $-0.039 + i 0.517$ |
FIG. 1: $\Xi^-p$ elastic cross section, in mb, as a function of the laboratory $\Xi$ momentum, in GeV/c. The two experimental data are taken from Ref. [12], black circle, and Ref. [13], black square (both are in-medium experimental data). The solid line indicates an upper limit for the cross section extracted in Ref. [5] with a large uncertainty in the momentum.
FIG. 2: $\Xi^- p \rightarrow \Lambda\Lambda$ cross section, in mb, as a function of the laboratory $\Xi$ momentum, in GeV/c. The experimental data is taken from Ref. [5].
FIG. 3: $\Xi^- p \rightarrow \Xi^0 n$ cross section, in mb, as a function of the laboratory $\Xi$ momentum, in GeV/c. The experimental data are taken from Ref. [5] as explained in the text.
FIG. 4: ΛΛ cross section, in mb, as a function of the laboratory Λ momentum, in GeV/c.

Figure 4