Chiral Dynamics and the $S_{11}(1535)$ Nucleon Resonance

N. Kaiser, P.B. Siegel**, and W. Weise

Physik Department, Technische Universität München

Institut für Theoretische Physik, D-85747 Garching, Germany

Abstract

The $SU(3)$ chiral effective lagrangian at next-to-leading order is applied to the S-wave meson-baryon interaction in the energy range around the ηN threshold. Potentials are derived from this lagrangian and used in a coupled channel calculation of the πN, ηN, $K\Lambda$, $K\Sigma$ system in the isospin-1/2, $l = 0$ partial wave. Using the same parameters as obtained from a fit to the low energy $\overline{K}N$ data it is found that a quasi-bound $K\Sigma$-state is formed, with properties remarkably similar to the $S_{11}(1535)$ nucleon resonance. In particular, we find a large partial decay width into ηN consistent with the empirical data.

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I. INTRODUCTION

The nucleon resonance $S_{11}(1535)$ has the outstanding property of a very strong ηN decay channel. The proper understanding of the low energy eta-nucleon interaction and threshold eta production consequently hinges on a correct description of the $S_{11}(1535)$ resonance. Recently precise eta photoproduction data off protons and nuclei close to threshold have become available. At MAMI (Mainz) [1] very precise angular distributions for the reaction $\gamma p \to \eta p$ have been measured from threshold at 707 MeV up to 800 MeV photon lab energy. Together with an analogous experiment using virtual photons (electroproduction) performed at ELSA (Bonn) [2] the data cover the whole range of the $S_{11}(1535)$ resonance. The measured cross sections clearly exhibit the strong $S_{11}(1535)$ dominance of near threshold η-production. Furthermore, the cross sections for the η-photoproduction off nuclei [3] show an $A^{2/3}$-dependence on the mass number A, characteristic of strong, surface-dominated interactions. Certainly, these new data demand a closer look at this particular nucleon resonance.

The traditional picture of the $S_{11}(1535)$ is that of an excited three quark nucleon resonance, with one of three quarks orbiting in an $l = 1$ state around the other two. This approach has however difficulties in explaining the large $(30-55\%)$ ηN branching ratio. In [4] the tensor force from the hyperfine interactions due to one-gluon exchange can produce the required SU(6) mixing to cause a large coupling to the ηN channel for the $S_{11}(1535)$ and a near-zero coupling for the $S_{11}(1650)$. However, then there are problems in reproducing the observed total decay width.

At present a frequently used ansatz for incorporating the $S_{11}(1535)$ resonance into the πN, ηN (and γN) system is to couple these channels directly to the $S_{11}(1535)$ via a phenomenological isobar model [5], [6] with background terms [7,8]. In these models, the coupling constants $g_{\pi N N^*}$ and $g_{\eta N N^*}$ are treated as free parameters. Their values vary in the literature, but always $g_{\eta N N^*}$ is the larger of the two. The physical reason behind the large coupling of the $S_{11}(1535)$ to the ηN channel is not understood.

In this letter, we investigate the possibility that the $S_{11}(1535)$ is a quasi-bound meson-baryon S-wave resonance. The basis of our calculation is the $SU(3)$ effective chiral lagrangian, with explicit symmetry breaking due to the non-vanishing up, down and strange quark masses properly incorporated. This approach successfully describes the $\Lambda(1405)$ resonance as a quasi-bound $\overline{K}N$ state [9]. Using the same lagrangian parameters as determined from our $\overline{K}N$ analysis, we extend the formalism to the energy range 1480 MeV $< \sqrt{s} <$ 1600 MeV to explore whether any $l = 0$, $I = 1/2$ resonances can be formed, and what their properties are. Indeed, we find a resonant state with a large ηN decay width as well as other characteristic properties of the $S_{11}(1535)$.

II. EFFECTIVE CHIRAL LAGRANGIAN AND PSEUDO-POTENTIAL APPROACH

The effective chiral lagrangian for meson-baryon interaction can be systematically expanded in powers of small external momenta [10]

$$\mathcal{L} = \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \cdots \tag{1}$$

where the superscript denotes the power of the meson momentum appearing in each term. In the heavy baryon mass formalism [11], the leading piece at order q reads

$$\mathcal{L}^{(1)} = \mathrm{tr}(\overline{B} i v \cdot D B) \tag{2}$$

with the chiral covariant derivative $D^\mu B = \partial^\mu B + [\Gamma^\mu, B]$. As this part of the lagrangian incorporates all current-algebra results of the meson-baryon interaction, it is refered to as the Weinberg-Tomozawa or current algebra term. At next order in the expansion scheme, q^2, there is a host of new terms allowed by chiral symmetry [12]. In the heavy baryon formalism the most general form relevant to S-wave scattering is given by [9]

$$\begin{aligned}\mathcal{L}^{(2)} = & \frac{1}{2M_0}\mathrm{tr}(\overline{B}((v\cdot D)^2 - D^2)B) \\ & + b_D \mathrm{tr}(\overline{B}\{\chi_+, B\}) + b_F \mathrm{tr}(\overline{B}[\chi_+, B]) + b_0 \mathrm{tr}(\overline{B}B)\mathrm{tr}(\chi_+) \\ & + d_D \mathrm{tr}(\overline{B}\{(A^2 + (v\cdot A)^2), B\}) + d_F \mathrm{tr}(\overline{B}[(A^2 + (v\cdot A)^2), B]) \\ & + d_0 \mathrm{tr}(\overline{B}B) Tr(A^2 + (v\cdot A)^2) \\ & + d_1 (\mathrm{tr}(\overline{B}A_\mu)\mathrm{tr}(A^\mu B) + \mathrm{tr}(\overline{B}(v\cdot A))\mathrm{tr}((v\cdot A)B)) \\ & + d_2 \mathrm{tr}(\overline{B}(A_\mu B A^\mu + (v\cdot A)B(v\cdot A)))\,.\end{aligned} \tag{3}$$

The first term above is a relativistic correction involving the baryon mass M_0 in the chiral limit. The parameters $b_D = 0.066$ GeV^{-1} and $b_F = -0.213$ GeV^{-1} are determined from the mass splittings in the baryon octet. The other six parameters have been determined in a fit to the low energy $\overline{K}N$ experimental data [9], constrained by some πN and KN data.

In order to investigate the possibility of resonance formation, one needs a non-perturbative approach which resums a set of diagrams to all orders. Since this leads necessarily beyond the systematic expansion scheme of chiral perturbation theory, we use a potential model. A pseudo-potential is constructed such that in the Born approximation it has the same S-wave scattering length as the effective chiral lagrangian, at order q^2. We note that this approach is quite similar to the one used in [13] for the nucleon-nucleon interaction.

As in [9] we examine two ways of parameterizing the finite range of the potential while keeping the Born term the same: a local potential and one separable in the incoming and outgoing center-of-mass momenta. The local potential between channels i and j is chosen to have a Yukawa form

$$V_{ij}(\vec{r}) = \frac{C_{ij}\alpha_{ij}^2}{8\pi f^2}\sqrt{\frac{M_i M_j}{s\omega_i\omega_j}}\frac{e^{-\alpha_{ij}r}}{r} \tag{4}$$

where the indices $i, j \in \{1,2,3,4\}$ label the four channels πN, ηN, $K\Lambda$ and $K\Sigma$ respectively. M_i and ω_i stand for the baryon mass and reduced meson-baryon energy in channel i, s is the squared center-of-mass total energy and $f = 92.4 \pm 0.3$ MeV the pion decay constant [14]. The parameters α_{ij} can be interpreted as average "effective masses" representing the spectrum of exchanged particles in the t-channel mediating the interaction. The relative interaction strengths C_{ij} which follow directly from the effective chiral lagrangian are listed in the appendix.

The potential of Eq.(4) is then inserted into the coupled channel Schrödinger equation

$$(\nabla^2 + k_i^2)\psi_i = 2\omega_i \sum_{j=1}^{4} V_{ij}\psi_j \tag{5}$$

to solve for the multi-channel S-matrix. For comparison we also examine a separable potential in momentum space, $\tilde{V}_{ij}(k_i, k_j) = C_{ij}\sqrt{M_i M_j / s\omega_i\omega_i}\, \alpha_i^2 \alpha_j^2 [4\pi^2 f^2 (\alpha_i^2 + k_i^2)(\alpha_j^2 + k_j^2)]^{-1}$, which is iterated in a corresponding Lippmann-Schwinger equation as described in [9].

III. DISCUSSION AND RESULTS

It is instructive first to discuss qualitative aspects of the calculation. The situation in the strangeness $S = 0$ sector at energies near the $K\Sigma$ threshold is similar to the $S = -1$ case near the $\overline{K}N$ threshold. There the $\Lambda(1405)$ resonance can be produced as a quasi-bound $\overline{K}N$ state resulting from the strong $I = 0$ attraction between the anti-kaon and the nucleon, as well as between the pion and sigma hyperon. This attractive interaction comes at leading order q from the current algebra term, Eq.(2). For the quantum numbers $S = 0$, $I = 1/2$ and $l = 0$ there are several important features:

- There is a strong attraction between the kaon and sigma (see the large negative coefficient C_{44} in the appendix). Thus, as soon as the inverse range parameter α exceeds a certain minimal value, a bound state will be necessarily formed below the $K\Sigma$ threshold.
- The direct interaction between the η meson and the nucleon is very weak and there is a small direct coupling between the πN and ηN channels (C_{22} and C_{12} are small).
- However, there is a strong coupling of both the πN and ηN channels to the $K\Sigma$ channel (C_{14} and C_{24} are sizable).
- Thus *the resonance formed will strongly connect the πN and ηN channels through the coupled channel dynamics.*

Let us for the moment consider only the current algebra piece, *i.e.* all b- and d-parameters are zero and the $1/M_0$ corrections are neglected. In this case $C_{22} = C_{12} = 0$, but C_{23} and C_{24} are large. In Table 1 we show the resonance energy versus α for both the local and separable potential using a common inverse range α for all channels. The resonance position is identified when an eigenphase of the multi-channel S-matrix is equal to 90 degrees. Thus, if $\alpha > 490$ MeV for the local potential (or 670 MeV for the separable one) a resonance is necessarily formed below the $K\Sigma$ threshold from the current algebra piece alone. Experimentally, there are two S_{11} nucleon resonances in this energy range, at 1535 and 1650 MeV. Since only the $S_{11}(1535)$ has a large ηN branching ratio it is the main candidate for this dynamically generated resonance.

Next we include all order q^2 terms using values of the b- and d-parameters as previously obtained from a fit to the low energy $\overline{K}N$ data and allow for a $\pm 5\%$ uncertainty in the parameters. We note that they are similar for both potential forms [9]. Thus the only free parameters are the α_{ij} in Eq.(4). Since the πN channel is far above its threshold a satisfactory fit to all the data using only one common range for all channels could not possibly be expected. However, a good fit was found using only two range parameters: one for the πN channel, and one common range for the other three. The off-diagonal ranges were taken to be $\alpha_{ij} = (\alpha_i + \alpha_j)/2$.

We performed a coupled channel calculation for the πN S_{11} phase shift and inelasticity, as well as the $\pi^- p \to \eta n$ cross section. The results of the fit for both the local and separable potential forms are shown in Figs.1 and 2a,b. Here the range parameters are $\alpha_{\pi N} = 320$ MeV and $\alpha_{\eta N} = \alpha_{K\Lambda} = \alpha_{K\Sigma} = 530$ MeV for the local potential. For the separable potential the range parameters are $\alpha_{\pi N} = 573$ MeV and $\alpha_{\eta N} = \alpha_{K\Lambda} = \alpha_{K\Sigma} = 776$ MeV. The values of b_0 and the d parameters, which only differ by 5% from [9], are listed in Table 2.

It is remarkable that such a good fit to the πN S_{11} phase shift and the η-production cross section is obtained with only two free parameters. Clearly, one can not expect the S_{11} inelasticity to be accurate since the $\pi\pi N$ channel is neglected here. Nevertheless, this picture of the $S_{11}(1535)$ as a dynamic resonance based on the effective chiral lagrangian reproduces many of its properties. For example we obtain a resonance mass $M^* = 1557$ MeV and a full width $\Gamma_{tot} = 179$ MeV. These values agree favorably with existing empirical determinations [14], [1]. As byproduct we extract the ηN S-wave scattering length to be $a_{\eta N} = (0.68 + i\,0.24)$ fm. This number is close to values found from other analyses [15,8,16].

In Fig.3 we display the $K\Sigma$ and $K\Lambda$ components of the bound state wave function at resonance. The root mean square radii are 0.70 fm and 0.88 fm for the $K\Sigma$ and $K\Lambda$ components.

IV. RESONANCE AND BACKGROUND EFFECTS

If there are only two reaction channels, it is often useful to parameterize the S-matrix in terms of its two eigenphases and a mixing angle ϵ. In the case of a pure Breit-Wigner resonance the T-matrix has the following energy dependence (on $W = \sqrt{s}$):

$$T(W) = \frac{1}{2(M^* - W) - i\,\Gamma(W)} \begin{pmatrix} \gamma_1 & \sqrt{\gamma_1\gamma_2} \\ \sqrt{\gamma_1\gamma_2} & \gamma_2 \end{pmatrix} , \tag{6}$$

with $\det T(W) = 0$. The constant M^* is the resonance mass and $\Gamma(W)$ the (energy dependent) width. For a S-wave resonance which decays into two-particle final states unitarity requires the energy dependence of the width to be $\Gamma(W) = \gamma_1\,k_1(W) + \gamma_2\,k_2(W)$. Here, $k_i(W)$ is the center-of-mass momentum in channel i and the constants γ_i are related to the partial decay widths $\gamma_i\,k_i(M^*)$. For a pure Breit-Wigner resonance, one eigenphase of the S-matrix (background) is zero and the other one (resonant) has the energy dependence

$$\tan\delta_{res}(W) = \frac{\Gamma(W)}{2(M^* - W)} . \tag{7}$$

Even though we do not have a pure Breit-Wigner resonance we find a resonant eigenphase (see Fig.4) which is very close to a Breit-Wigner form. In this figure, we plot both the resonant and non-resonant eigenphases versus pion lab kinetic energy for our calculation. The dots correspond to a Breit-Wigner form with parameters $M^* = 1557$ MeV, $\gamma_\pi = 0.26$ and $\gamma_\eta = 0.25$. These numbers result in partial decay widths $\Gamma_\pi = 124$ MeV and $\Gamma_\eta = 55$ MeV. The branching ratio $b_\eta = 0.31$ is still compatible with the existing analysis [14] whereas $b_\pi = 0.69$ is somewhat too large, presumably due to the neglect of the $\pi\pi N$ channel and our way of extracting γ_i. Here, the γ_i are determined from the energy dependence of the resonant eigenphase. We note furthermore that at the ηN-threshold ($W_{th} = M_N + m_\eta$) the πN S_{11} phase shift reads according to Eq.(7)

$$\tan \delta_{11}(W_{th}) = \frac{\gamma_\pi k_\pi(W_{th})}{2(M^* - W_{th})} \tag{8}$$

within the two-channel calculation, since the background phase is zero at W_{th}. Therefore a good knowledge of this particular phase constrains the resonance mass and the πN partial decay width.

From the T-matrix for a pure Breit-Wigner resonance in Eq.(6), the ratio of cross sections for scattering from channel $1 \to 2$ divided by that for elastic scattering ($1 \to 1$) is $\sigma_{21}(W)/\sigma_{11}(W) = \gamma_2\, k_2(W)/\gamma_1\, k_1(W)$. Therefore, the ratio R_{BW} defined as

$$R_{BW} \equiv \frac{\gamma_1\, k_1(W)\, \sigma_{21}(W)}{\gamma_2\, k_2(W)\, \sigma_{11}(W)}\,, \tag{9}$$

is exactly one for a pure Breit-Wigner resonance. Any deviation from unity originates from the background eigenphase, assuming that the resonant eigenphase has well determined partial widths. In Fig. 5 we plot the quantity

$$R_{BW} = \frac{\gamma_\pi k_\pi\, \sigma(\pi N \to \eta N, S_{11})}{\gamma_\eta k_\eta\, \sigma(\pi N \to \pi N, S_{11})} \tag{10}$$

which involves S_{11} partial wave cross sections only, versus the pion lab kinetic energy. The solid line corresponds to the potential model used here. Since the η-production near threshold is strongly S-wave dominated, one can identify $\sigma(\pi N \to \eta N, S_{11})$ with $\frac{3}{2}\sigma(\pi^- p \to \eta n)$. The S_{11} component of the elastic πN cross section can be constructed from the partial wave analysis of [17,18]. Using these inputs together with $\gamma_\pi/\gamma_\eta = 1.04$ as determined from the shape of our resonant eigenphase, we display the result for this ratio. Since presently the branching ratios b_π, b_η have large uncertainties, we choose for reasons of comparison the values obtained here. The error bars in Fig.5 reflect only those of η-production data. It is visible that R_{BW} deviates from unity as required for a pure Breit-Wigner resonance. This is an indication that background effects (corresponding to a non-resonant eigenphase) are not negligible. In [8] a similar phenomenon was observed in sofar as the coupling constants of the resonance depended strongly on the treatment of the background (nonresonant) amplitude. Also in [19] the coupling constants of the $S_{11}(1535)$ had to be varied up to 20% from the values obtained from the widths in order to obtain a good fit the the scattering data. This all points towards the presence of some background amplitude. We remark however that inclusion of the $\pi\pi N$ channel in our analysis would change the branching ratios and could considerably lower the ratio R_{BW} from the value shown in Fig.5. If possible an experimental determination of this ratio would be very valuable.

In summary, we have used the effective chiral lagrangian at next-to-leading order to investigate the possibility that the $S_{11}(1535)$ resonance is a quasi-bound $K\Sigma$-$K\Lambda$ state. Using the same parameters as obtained from fitting the low energy $\overline{K}N$ data and two free finite range parameters, a resonance can be formed at 1557 MeV with the characteristic properties of the $S_{11}(1535)$. The πN S_{11} phase shifts and inelasticities as well as the ηN-production cross section are remarkably well reproduced. The dynamically generated resonance has a full width of 179 MeV and branching ratios extracted from the shape of the resonance of 69% into πN and 31% into ηN final states. Furthermore, we elaborated on the background effects in the reactions dominated by the $S_{11}(1535)$ and proposed as a measure for it the ratio R_{BW} in Eq.(10). The coupled channel approach presented here can also be used in calculations of the η-photoproduction process, and we hope to report on this topic in the near future.

Appendix

Here we list the expressions of the relative coupling strengths C_{ij} in the $I = 1/2$ basis entering the potential of Eq.(4) in terms of the chiral lagrangian parameters. The indices $1, 2, 3, 4$ refer to the πN, ηN, $K\Lambda$, $K\Sigma$ channel respectively and the η-particle is identified with the $SU(3)$-octet state η_8. Furthermore, E denotes the center-of-mass meson energy and $M_0 \simeq 0.91$ GeV is the octet baryon mass in the chiral limit.

$$
\begin{aligned}
C_{11} &= -E_\pi + \frac{1}{2M_0}(m_\pi^2 - E_\pi^2) + 2m_\pi^2(b_D + b_F + 2b_0) - E_\pi^2(d_D + d_F + 2d_0) \\
C_{12} &= 2m_\pi^2(b_D + b_F) + E_\pi E_\eta(d_2 - d_D - d_F) \\
C_{13} &= \frac{3}{8}(E_\pi + E_K) + \frac{3}{16M_0}(E_\pi^2 - m_\pi^2 + E_K^2 - m_K^2) - \frac{1}{2}(m_K^2 + m_\pi^2)(b_D + 3b_F) \\
&\quad + \frac{E_\pi E_K}{2}(d_D + 3d_F - d_2) \\
C_{14} &= -\frac{1}{8}(E_\pi + E_K) - \frac{1}{16M_0}(E_\pi^2 - m_\pi^2 + E_K^2 - m_K^2) + \frac{1}{2}(b_F - b_D)(m_\pi^2 + m_K^2) \\
&\quad + \frac{E_\pi E_K}{2}(d_D - d_F - 2d_1 - 3d_2) \\
C_{22} &= \frac{16}{3}m_K^2(b_D - b_F + b_0) + 2m_\pi^2(\frac{5}{3}b_F - b_D - \frac{2}{3}b_0) + E_\eta^2(d_F - \frac{5}{3}d_D - 2d_0 + \frac{2}{3}d_2) \qquad (11) \\
C_{23} &= \frac{3}{8}(E_\eta + E_K) + \frac{3}{16M_0}(E_K^2 - m_K^2 + E_\eta^2 - m_\eta^2) + (b_D + 3b_F)(\frac{5}{6}m_K^2 - \frac{1}{2}m_\pi^2) \\
&\quad - E_\eta E_K(\frac{d_F}{2} + \frac{d_D}{6} + d_1 + \frac{5d_2}{6}) \\
C_{24} &= \frac{3}{8}(E_\eta + E_K) + \frac{3}{16M_0}(E_K^2 - m_K^2 + E_\eta^2 - m_\eta^2) + (\frac{5}{2}m_K^2 - \frac{3}{2}m_\pi^2)(b_F - b_D) \\
&\quad + \frac{E_\eta E_K}{2}(d_D - d_F - d_2) \\
C_{33} &= (\frac{10}{3}b_D + 4b_0)m_K^2 + E_K^2(\frac{2d_2}{3} - 2d_0 - \frac{5d_D}{3}) \\
C_{34} &= 2m_K^2 b_D + E_K^2(d_2 - d_D) \\
C_{44} &= -E_K - \frac{1}{2M_0}(E_K^2 - m_K^2) + 2m_K^2(b_D - 2b_F + 2b_0) + E_K^2(2d_F - d_D - 2d_0)
\end{aligned}
$$

Local Potential		Separable Potential	
α (MeV)	Energy	α (MeV)	Energy
490	1661	670	1661
520	1604	710	1604
550	1550	750	1556
575	1489	760	1501

Table 1. The energy of the $K\Sigma$-$K\Lambda$ ($I = 1/2$) quasi-bound state produced from the current algebra (Weinberg-Tomozawa) term alone as a function of the range parameter α for both the local and the separable potential. The range parameter α is the same for all channels.

Potential	b_0	d_0	d_D	d_F	d_1	d_2	$\alpha_{\pi N}$	$\alpha_{K\Sigma}$
Local	–0.517	–0.68	–0.02	–0.28	+0.22	–0.41	0.32	0.53
Separable	–0.279	–0.42	–0.23	–0.41	+0.27	–0.65	0.57	0.77

Table 2. Values of the Lagrange parameter entering at order q^2 in units of GeV^{-1}. The inverse ranges α are given in GeV.

Figure Captions

Fig.1 The cross section $\sigma(\pi^- p \to \eta n)$ versus the pion lab kinetic energy T_π. The selected data are taken from [20]. The solid/dashed line corresponds to the local/separable potential form.

Fig.2a The pion-nucleon S_{11} phase shift as a function of the pion lab kinetic energy. The triangles/circles are from the phase shift analysis of [17]/ [18]. The full/dashed curve corresponds to a calculation using a local/separable potential form.

Fig.2b The pion-nucleon S_{11} inelasticity as a function of the pion lab kinetic energy. The notation is the same as in Fig.2a.

Fig.3 The two-component bound state wave function at resonance versus the meson baryon distance r.

Fig.4 The eigenphases of the multi-channel S-matrix below the $K\Lambda$-threshold. The heavy dots correspond to a Breit-Wigner fit of the resonant phase.

Fig.5 The ratio R_{WB} defined in Eq.(10). The notation is the same as in Fig.2a. The error bars reflect only those of the η-production cross sections.

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