ELSEVIER

9 November 1995

PHYSICS LETTERS B

Physics Letters B 362 (1995) 23–28

Chiral dynamics and the $S_{11}(1535)$ nucleon resonance ★

N. Kaiser, P.B. Siegel [1], W. Weise

Physik Department, Technische Universität München,
Institut für Theoretische Physik, D-85747 Garching, Germany

Received 27 July 1995; revised manuscript received 13 September 1995
Editor: C. Mahaux

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. A potential is derived from this lagrangian and used in a coupled channel calculation of the πN, ηN, $K\Lambda$, $K\Sigma$ system in the isospin-$\frac{1}{2}$, $l = 0$ partial wave. Using the same parameters as obtained previously from a fit to the low energy $\bar{K}N$ data it is found that a quasi-bound $K\Sigma$-$K\Lambda$-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.

PACS: 14.20.Gk; 14.40.Aq; 14.20.Jn
Keywords: Chiral dynamics; Coupled channel S-matrix; Nucleon resonances; Eta meson production; Kaon-hyperon bound state

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 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 electroproduction experiment 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. 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 [3,4] the tensor force due to one-gluon exchange can produce the required state 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,

★ Work supported in part by BMBF and GSI.

[1] On sabbatical leave from California State Polytechnic University, Pomona, CA 91768, USA.

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SSDI 0370-2693(95)01203-6

the coupling constants $g_{\pi NN^*}$ and $g_{\eta NN^*}$ are treated as free parameters. Their values vary in the literature, but always $g_{\eta NN^*}$ is the larger of the two. The physical reason behind the large ηN coupling of the $S_{11}(1535)$ is not well 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 $SU(3)$ chiral effective 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 1.45 GeV $< \sqrt{s} <$ 1.6 GeV to explore whether any S_{11} 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 $S_{11}(1535)$.

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. In the heavy baryon mass formalism, the leading piece at order q reads

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

with the chiral covariant derivative $D^\mu B = \partial^\mu B + [\Gamma^\mu, B]$, where B denotes the $SU(3)$ baryon octet fields. This part of the lagrangian is referred to as the current algebra term. At next order in the expansion scheme, q^2, there is a host of new terms allowed by chiral symmetry. In the heavy baryon formalism the most general form relevant to S-wave scattering is given by [9]

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

Here $A_\mu = -\partial_\mu\phi/2f$ is the derivative of the octet matrix of pseudoscalar meson fields and $f = (92.4\pm0.3)$ MeV [11] is the pion decay constant. The first term above is a relativistic correction involving the baryon mass in the chiral limit, $M_0 \simeq 0.9$ GeV. The parameters $b_D = 0.066\ \mathrm{GeV}^{-1}$ and $b_F = -0.213\ \mathrm{GeV}^{-1}$ 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 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 (see [9] for details).

As in [9] we examine two ways of parameterizing the finite range of the potential: 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

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

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. 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,

Table 1
The energy of the $K\Sigma$-$K\Lambda$ ($I = \frac{1}{2}$) quasi-bound state produced from the current algebra term alone versus the range parameter α

Local potential		Separable potential	
α (MeV)	energy	α (MeV)	energy
520	1604	710	1604
550	1550	750	1556
575	1489	760	1501

$$\tilde{V}_{ij}(k_i, k_j) = C_{ij}\sqrt{\frac{M_i M_j}{s\omega_i\omega_i}}\frac{\alpha_i^2\alpha_j^2}{4\pi^2 f^2(\alpha_i^2+k_i^2)(\alpha_j^2+k_j^2)},$$

which is iterated in a Lippmann-Schwinger equation as described in [9].

It is instructive first to discuss qualitative aspects of the calculation. The situation at energies near the $K\Sigma$ threshold is similar to the case near the $\bar{K}N$ threshold investigated in [9]. There the $\Lambda(1405)$ resonance can be produced as a quasi-bound $\bar{K}N$ 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). In the S_{11}-channel there are several important features:

- There is a strong attraction between the kaon and sigma (see the large negative coefficient C_{44}). 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 sizeable).
- 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°. 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 candidate for this dynamically generated resonance.

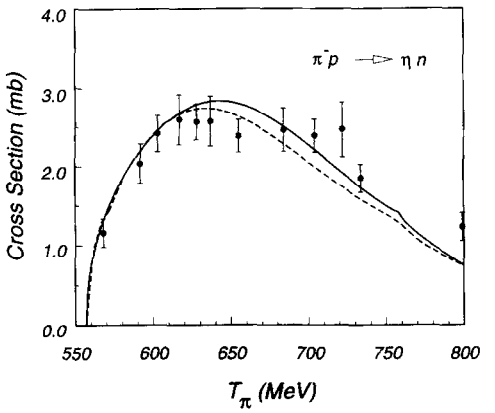

Fig. 1. The cross section $\sigma(\pi^- p \to \eta n)$ versus the pion lab kinetic energy T_π. The selected data are taken from [16]. The solid/dashed line corresponds to the local/separable potential form.

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 $\bar{K}N$ data and allow for a ±5% uncertainty in the parameters. 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 $\alpha_{ij} = \frac{1}{2}(\alpha_i + \alpha_j)$.

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, 2b. 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 $\alpha_{K\Sigma} = 776$

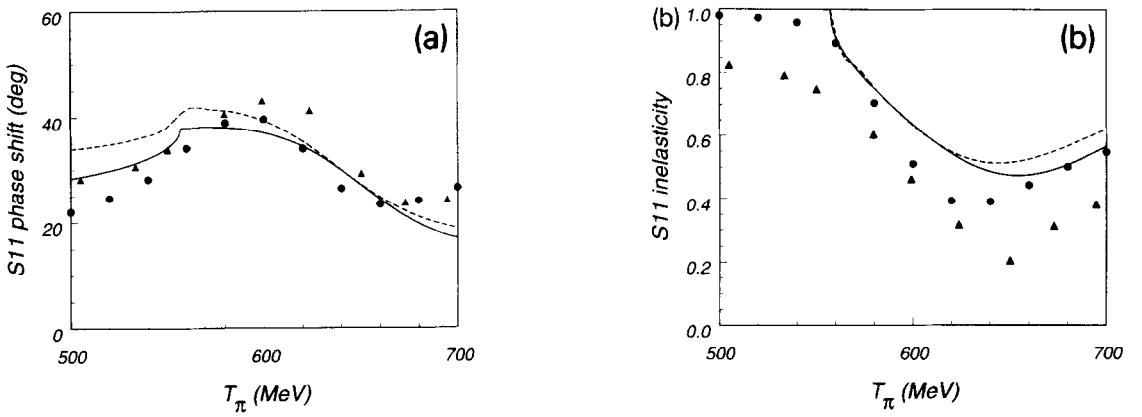

Fig. 2. (a) The pion-nucleon S_{11} phase shift as a function of the pion lab kinetic energy. The triangles/circles are from the phase shift analysis of [13]/ [14]. The full/dashed curve corresponds to a calculation using a local/separable potential form. (b) The pion-nucleon S_{11} inelasticity as a function of the pion lab kinetic energy. The notation is the same as in (a).

Table 2
Values of the lagrange parameters in units of GeV^{-1}. The inverse ranges α are given in GeV

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

MeV. The values of b_0 and the d parameters, which differ by only 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 $\Gamma_{\rm tot} = 179$ MeV. These values agree favorably with existing empirical determinations [11,1]. 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 [12,8,4].

In the case of a pure Breit-Wigner resonance the T-matrix has the following energy dependence (on $W = \sqrt{s}$):

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

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 $\tan\delta_{\rm res}(W) = \Gamma(W)/2(M^* - W)$. In Fig. 3 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 [11] 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. For a pure Breit-Wigner resonance the ra-

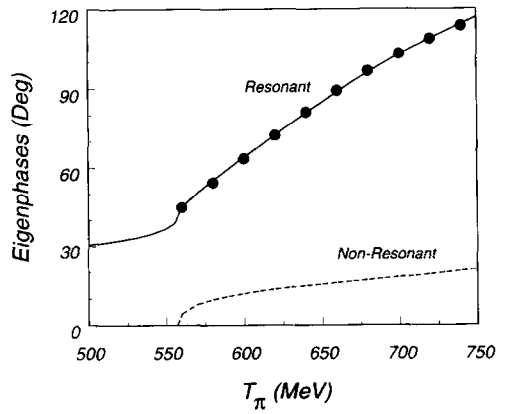

Fig. 3. The eigenphases of the multi-channel S-matrix below the $K\Lambda$-threshold.

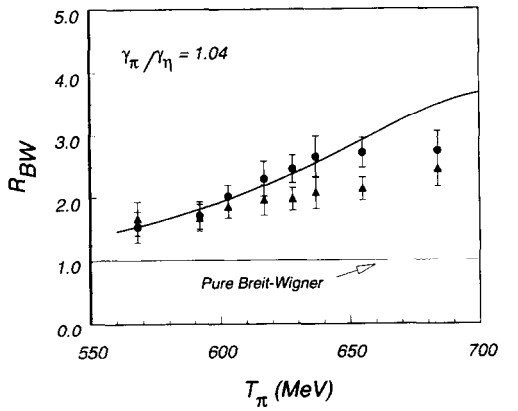

Fig. 4. The ratio $R_{\rm WB}$ defined in Eq. (7). The notation is the same as in Fig. 2a. The error bars reflect only those of the η production cross sections.

tio $R_{\rm BW} = \gamma_1 k_1(W)\sigma_{21}(W)/\gamma_2 k_2(W)\sigma_{11}(W)$ with $\sigma_{21}(W)/\sigma_{11}(W)$ the ratio of cross sections for scattering from channel $1 \to 2$ divided by that for elastic scattering ($1 \to 1$) is exactly one. Any deviation from unity originates from the background eigenphase. In Fig. 4 we plot the quantity

$$R_{\rm BW} = \frac{\gamma_\pi k_\pi\, \sigma(\pi N \to \eta N, S_{11})}{\gamma_\eta k_\eta\, \sigma(\pi N \to \pi N, S_{11})}\,, \qquad (7)$$

which involves S_{11} partial wave cross sections only. 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 is constructed from the partial wave analysis of [13,14]. Since presently the branching ratios b_π, b_η have large uncertainties, we choose for reasons of comparison the value $\gamma_\pi/\gamma_\eta = 1.04$ as obtained here. It is visible that $R_{\rm BW}$ deviates from unity which indicates that background effects (corresponding to a non-resonant eigenphase) are not negligible. In [8] a similar phenomenon was observed in so far as the coupling constants of the resonance depended strongly on the treatment of the background (nonresonant) amplitude. Also in [15] 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 to the scattering data.

In summary, we have used the $SU(3)$ chiral effective 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 $\bar{K}N$ data and two 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 them the ratio $R_{\rm BW}$ in Eq. (7).

Appendix

Here we list the expressions of the relative coupling strengths C_{ij} in the $I = \frac{1}{2}$ basis entering the potential of Eq. (4). The indices 1,2,3,4 refer to the πN, ηN, $K\Lambda$, $K\Sigma$ channel, respectively, and E denotes the center-of-mass meson energy.

$$C_{11} = -E_\pi + \frac{1}{2M_0}(m_\pi^2 - E_\pi^2) + 2m_\pi^2(b_D + b_F + 2b_0) - E_\pi^2(d_D + d_F + 2d_0)\,,$$

$$C_{12} = 2m_\pi^2(b_D + b_F) + E_\pi E_\eta(d_2 - d_D - d_F)\,,$$

$$C_{13} = \tfrac{3}{8}(E_\pi + E_K) + \frac{3}{16M_0}(E_\pi^2 - m_\pi^2 + E_K^2 - m_K^2)$$
$$- \tfrac{1}{2}(m_K^2 + m_\pi^2)(b_D + 3b_F)$$
$$+ \tfrac{1}{2}E_\pi E_K(d_D + 3d_F - d_2)\,,$$

$$C_{14} = -\tfrac{1}{8}(E_\pi + E_K)$$
$$- \frac{1}{16M_0}(E_\pi^2 - m_\pi^2 + E_K^2 - m_K^2)$$
$$+ \tfrac{1}{2}(b_F - b_D)(m_\pi^2 + m_K^2)$$
$$+ \tfrac{1}{2}E_\pi E_K(d_D - d_F - 2d_1 - 3d_2)\,,$$

$$C_{22} = \tfrac{16}{3}m_K^2(b_D - b_F + b_0)$$
$$+ 2m_\pi^2(\tfrac{5}{3}b_F - b_D - \tfrac{2}{3}b_0)$$
$$+ E_\eta^2(d_F - \tfrac{5}{3}d_D - 2d_0 + \tfrac{2}{3}d_2)\,,$$

$$C_{23} = \tfrac{3}{8}(E_\eta + E_K)$$
$$+ \frac{3}{16M_0}(E_K^2 - m_K^2 + E_\eta^2 - m_\eta^2)$$
$$+ (b_D + 3b_F)(\tfrac{5}{6}m_K^2 - \tfrac{1}{2}m_\pi^2)$$
$$- E_\eta E_K(\tfrac{1}{2}d_F + \tfrac{1}{6}d_D + d_1 + \tfrac{5}{6}d_2)\,,$$

$$C_{24} = \tfrac{3}{8}(E_\eta + E_K)$$
$$+ \frac{3}{16M_0}(E_K^2 - m_K^2 + E_\eta^2 - m_\eta^2)$$
$$+ (\tfrac{5}{2}m_K^2 - \tfrac{3}{2}m_\pi^2)(b_F - b_D)$$
$$+ \tfrac{1}{2}E_\eta E_K(d_D - d_F - d_2)\,,$$

$$C_{33} = (\tfrac{10}{3}b_D + 4b_0)m_K^2 + E_K^2(\tfrac{2}{3}d_2 - 2d_0 - \tfrac{5}{3}d_D)\,,$$

$$C_{34} = 2m_K^2 b_D + E_K^2(d_2 - d_D)\,,$$

$$C_{44} = -E_K - \frac{1}{2M_0}(E_K^2 - m_K^2)$$
$$+ 2m_K^2(b_D - 2b_F + 2b_0)$$
$$+ E_K^2(2d_F - d_D - 2d_0)\,.$$

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