Opposite parity fermion mixing and baryons $1/2^\pm$

A.E. Kaloshin and E.A. Kobeleva

Irkutsk State University

V.P. Lomov

The Institute for System Dynamics and Control Theory of SB RAS

We develop a variant of $K$-matrix, which includes the effect of opposite parity fermions (OPF) mixing, and apply it for description of $\pi N$ partial waves $S_{11}$ and $P_{11}$. OPF-mixing leads to appearance of negative energy poles in $K$-matrix and restoration of MacDowell symmetry, relating two partial waves. Joint analysis of PWA results for $S_{11}$ and $P_{11}$ confirms significance of this effect.

I. INTRODUCTION

For fermions there exists a non-standard mixing, when fermion fields with opposite parities are mixing at loop level while parity is conserved in vertex (shortly OPF-mixing):

\[ N_1(1/2^-) \rightarrow N_2(1/2^+) \]

It is possible because fermion and antifermion have different parities. This effect was investigated in detail in [1] and was applied to $\pi N$ scattering, where it leads to relation between two partial waves. In [1] was found the simplest physical example of manifestation of this effect: the partial waves $P_{13}$ and $D_{13}$, where baryons $J = 3/2^\pm$ are produced. The OPF-mixing effect is identified in the partial wave $P_{13}$ as rather specific interference of resonance with background generated by resonance state in $D_{13}$ wave. The above-mentioned relation between partial waves influences mainly on a wave with lower orbital momentum and it is used as additional source of information about structure of wave with higher $l$.

Another physical example, where OPF-mixing may be essential, is related with the partial waves $S_{11}$ and $P_{11}$, where resonances $J^P = 1/2^\pm, I = 1/2$ are produced. Most interesting object here is the Roper resonance $N(1440)$, which has some unusual properties and problems with quark-models identification, see, e.g. [2–10]. However, in presence of several resonance states the approach of [1], that uses a matrix propagator, becomes too cumbersome. Alternatively, for description of OPF-mixing one can use the $K$-matrix approach, which works for any number of states and channels.

In this paper we develop the $K$-matrix approach for $\pi N$ partial amplitudes with accounting of the OPF-mixing effect and apply it for description of $S_{11}$ and $P_{11}$ partial waves. Most serious
changing as compared with its standard form is the appearance of negative energy poles in $K$-matrix. If, besides, we use QFT to calculate tree amplitudes (i.e. $K$-matrix), starting from effective Lagrangians, we obtain the partial amplitudes $\pi N \rightarrow \pi N$ satisfying the MacDowell symmetry condition:

$$f_{l+}(W) = -f_{l+1,-}(-W),$$

which was obtained \([11]\) from general analytic properties of amplitudes.

We use the obtained $K$-matrix to describe results of partial wave analysis for $S_{11}$ and $P_{11}$ amplitudes. The main purpose is to see the manifestation of OPF-mixing and it naturally leads to joint fitting of these two waves.

## II. MIXING OF FERMIONS WITH OPPOSITE PARITIES AND $K$-MATRIX

We need to discuss the effect of OPF-mixing in amplitudes of $\pi N$ scattering and its implementation in framework of $K$-matrix description. For a first step one may restrict oneself by a simplified case: two resonance states and two channels. Let us write down the effective Lagrangians $\pi NN'$ without derivatives and conserving the parity:

$$\mathcal{L}_{\text{int}} = g_1 \bar{N}_1(x) N(x) \varphi(x) + \text{h.c.}, \quad \text{for } J^P(N_1) = 1/2^-, \quad (2)$$

$$\mathcal{L}_{\text{int}} = ig_2 \bar{N}_2(x) \gamma^5 N(x) \varphi(x) + \text{h.c.}, \quad \text{for } J^P(N_2) = 1/2^+. \quad (3)$$

Let us consider two baryon states of opposite parities with masses $m_1$ ($J^P = 1/2^-$), $m_2$ ($J^P = 1/2^+$) and two intermediate states $\pi N$, $\eta N$. Using the effective Lagrangians we can calculate contributions of states $N_1$, $N_2$ to partial waves at tree level (see details in \([1]\)) for $s$-wave amplitudes:

$$f^{\text{tree}}_{s,+}(\pi N \rightarrow \pi N) = \frac{(E_N^{(\pi)} + m_N)}{8\pi W} \left( \frac{g^2_{1,\pi}}{W - m_1} + \frac{g^2_{2,\pi}}{W + m_2} \right),$$

$$f^{\text{tree}}_{s,+}(\pi N \rightarrow \eta N) = -\sqrt{\frac{(E_N^{(\pi)} + m_N)(E_N^{(\eta)} + m_N)}{8\pi W}} \left( \frac{g_{1,\pi}g_{1,\eta}}{W - m_1} + \frac{g_{2,\pi}g_{2,\eta}}{W + m_2} \right),$$

$$f^{\text{tree}}_{s,+}(\eta N \rightarrow \eta N) = -\frac{(E_N^{(\eta)} + m_N)}{8\pi W} \left( \frac{g^2_{1,\eta}}{W - m_1} + \frac{g^2_{2,\eta}}{W + m_2} \right),$$

and for $p$-wave amplitudes:

$$f^{\text{tree}}_{p,-}(\pi N \rightarrow \pi N) = \frac{(E_N^{(\pi)} - m_N)}{8\pi W} \left( \frac{g^2_{1,\pi}}{-W - m_1} + \frac{g^2_{2,\pi}}{-W + m_2} \right),$$

$$f^{\text{tree}}_{p,-}(\pi N \rightarrow \eta N) = \sqrt{\frac{(E_N^{(\pi)} - m_N)(E_N^{(\eta)} - m_N)}{8\pi W}} \left( \frac{g_{1,\pi}g_{1,\eta}}{-W - m_1} + \frac{g_{2,\pi}g_{2,\eta}}{-W + m_2} \right),$$

$$f^{\text{tree}}_{p,-}(\eta N \rightarrow \eta N) = \frac{(E_N^{(\eta)} - m_N)}{8\pi W} \left( \frac{g^2_{1,\eta}}{-W - m_1} + \frac{g^2_{2,\eta}}{-W + m_2} \right).$$
Here $W = \sqrt{s}$ is the total CMS energy and $E_N^{(\pi)} (E_N^{(\eta)})$ is nucleon CMS energy of system $\pi N (\eta N)$

$$E_N^{(\pi)} = \frac{W^2 + m_N^2 - m_\pi^2}{2W}. \quad (6)$$

We introduced here short notation for coupling constants, e.g. $g_{1,\pi} = g_{N_1 N_\pi}$.

The tree amplitudes (4)–(5) contain poles with both positive and negative energy, originated from propagators of $N_1$ and $N_2$ fields of opposite parities. Accounting the loop transitions results in dressing of states and also in mixing of these two fields.

Note that $W \rightarrow -W$ replacement gives

$$E_N^{(\pi)} + m_N \rightarrow -(E_N^{(\pi)} - m_N), \quad (7)$$

so tree amplitudes (4)–(5) possess the MacDowell symmetry property [11]

$$f_{p,-}(W) = -f_{s,+}(-W). \quad (8)$$

In $K$-matrix representation for partial amplitudes

$$f = K \left( 1 - iPK \right)^{-1}, \quad (9)$$

diagonal matrix $iP$, constructed from CMS momenta, originates from imaginary part of a loop. Therefore, $K$-matrix here is simply a matrix of tree amplitudes that should be identified with amplitudes (4),(5).

As the result we come to representation of partial amplitudes for $s$- and $p$-waves

$$f_s(W) = K_s(W) \left( 1 - iPK_s(W) \right)^{-1}, \quad f_p(W) = K_p(W) \left( 1 - iPK_p(W) \right)^{-1}, \quad (10)$$

where the matrices $K_s, K_p$ (i.e. tree amplitudes (4),(5)), may be written in factorized form [1]

$$K_s = -\frac{1}{8\pi} \rho_s \hat{K}_s \rho_s, \quad K_p = \frac{1}{8\pi} \rho_p \hat{K}_p \rho_p. \quad (11)$$

Here $\rho_s, \rho_p$ are

$$\rho_s(W) = \begin{pmatrix} \sqrt{\frac{E_N^{(\pi)} + m_N}{W}}, & 0 \\ 0, & \sqrt{\frac{E_N^{(\eta)} + m_N}{W}} \end{pmatrix}, \quad \rho_p(W) = \begin{pmatrix} \sqrt{\frac{E_N^{(\pi)} - m_N}{W}}, & 0 \\ 0, & \sqrt{\frac{E_N^{(\eta)} - m_N}{W}} \end{pmatrix}. \quad (12)$$

[1] Similar $K$-matrix have been used for a long time in $\pi N$ phenomenology, see, e.g. [12], but with other phase-space factors.
and matrix $P$ consists of CMS momenta as analytic functions of $W$. In this case "primitive" $K$-matrices contain poles with both positive and negative energy

$$
\hat{K}_s(W) = \left( \begin{array}{ccc} \frac{g_{1,\pi}^2}{W - m_1} + \frac{g_{2,\pi}^2}{W + m_2} & \frac{g_{1,\pi}g_{2,\eta}}{W - m_1} & \frac{g_{2,\pi}g_{2,\eta}}{W + m_2} \\
\frac{g_{1,\pi}g_{2,\eta}}{W - m_1} & \frac{g_{1,\eta}^2}{W - m_1} & \frac{g_{2,\eta}^2}{W + m_2} \\
\frac{g_{2,\pi}g_{2,\eta}}{W - m_1} & \frac{g_{1,\eta}g_{2,\eta}}{W - m_1} & \frac{g_{2,\eta}^2}{W + m_2} \end{array} \right),
$$

(13)

$$
\hat{K}_p(W) = \hat{K}_s(-W) = \left( \begin{array}{ccc} \frac{g_{1,\pi}^2}{-W - m_1} + \frac{g_{2,\pi}^2}{-W + m_2} & \frac{g_{1,\pi}g_{2,\eta}}{-W - m_1} & \frac{g_{2,\pi}g_{2,\eta}}{-W + m_2} \\
\frac{g_{1,\pi}g_{2,\eta}}{-W - m_1} & \frac{g_{1,\eta}^2}{-W - m_1} & \frac{g_{2,\eta}^2}{-W + m_2} \\
\frac{g_{2,\pi}g_{2,\eta}}{-W - m_1} & \frac{g_{1,\eta}g_{2,\eta}}{-W - m_1} & \frac{g_{2,\eta}^2}{-W + m_2} \end{array} \right).
$$

(14)

Recall that $m_1$ is mass of $J^P = 1/2^-$ state and $m_2$ is mass of $J^P = 1/2^+$ one. Generalization of this construction for the case of more channels and states is obvious.

Since CMS momenta have the property $P(-W) = -P(W)$, the MacDowell symmetry property (8) is extended from tree amplitudes to unitarized $K$-matrix ones (10). Note that our $K$-matrix amplitudes (10) may be rewritten in other form, close to the one used in (12)

$$
f_s(W) = -\frac{1}{8\pi\rho_s} \hat{K}_s[1 + i\rho_s P \rho_s \hat{K}_s(W)/(8\pi)]^{-1} \rho_s,
$$

$$
f_p(W) = \frac{1}{8\pi\rho_p} \hat{K}_p[1 - i\rho_p P \rho_p \hat{K}_p(W)/(8\pi)]^{-1} \rho_p.
$$

(15)

Following a common sense one can expect that presence of negative energy pole, for example, in elastic $\pi N$ amplitude should give a negligible effect in physical energy region. However, this is not true if corresponding coupling constant is large $|g_{2,\pi}| \gg |g_{1,\pi}|$. To see the reason of this ratio, one can compare decay widths of $s$- and $p$-states

$$
\Gamma(N_1 \to \pi N) = g_{N_1,\pi N}^2 \Phi_s, \quad \Gamma(N_2 \to \pi N) = g_{N_2,\pi N}^2 \Phi_p,
$$

(16)

where $\Phi_s$, $\Phi_p$ are corresponding phase volumes. For resonance states not far from threshold, with masses, e.g. 1.5–1.7 GeV, phase volumes differ greatly, $\Phi_s \gg \Phi_p$. If both resonances have typical hadronic width $\Gamma \sim 100$ MeV, then coupling constants differ dramatically too, $|g_{N_2,\pi N}| \gg |g_{N_1,\pi N}|$. This inequality will result in increasing of background contribution to $s$-wave and on the other hand in suppressing of background in $p$-wave. As a result, OPF-mixing leads to relation between two partial wave of $\pi N$ scattering, but this connection mainly influences on amplitude with lower orbital number.

Above we use the simplest effective Lagrangians (2)–(3) to derive tree amplitudes. However, it is well-known, that spontaneous breaking of chiral symmetry requires pion field to appear in Lagrangian only through derivative

$$
\mathcal{L}_{\text{int}} = f_2 \bar{N}_2(x) \gamma^5 \gamma^\mu N(x) \partial_\mu \varphi(x) + \text{h.c.}, \quad J^P = 1/2^+, \quad f_2 = \frac{g_2}{m_2 + m_N}.
$$

(17)
It is not difficult to understand how inclusion of derivative changes tree amplitudes and, hence $K$-matrix. Pole contribution $\pi(k_1)N(p_1) \rightarrow N_2(p) \rightarrow \pi(k_2)N(p_2)$ in that case takes the form:

$$T = f_2^2 \bar{u}(p_2) \gamma^5 \hat{k}_2 \frac{1}{\hat{p} - M} \gamma^5 \hat{k}_1 u(p_1).$$

(18)

With use of equations of motion, we see that inclusion of derivative at vertex leads to the following modification of resonance contribution

$$g_2^2 \frac{1}{\hat{p} - M} \rightarrow f_2^2 (\hat{p} + m_N) \frac{1}{\hat{p} - M} (\hat{p} + m_N).$$

(19)

Separation of the positive and negative energy poles is performed with the off-shell projector operators $\Lambda^\pm = 1/2 (1 \pm \hat{p}/W)$

$$f_2^2 (\hat{p} + m_N) \frac{1}{\hat{p} - m_N} (\hat{p} + m_N) = \Lambda^+ f_2^2 (W + m_N)^2 \frac{1}{W - M} + \Lambda^- f_2^2 (W - m_N)^2 \frac{1}{W - M},$$

(20)

where the first term gives contribution to $p$-wave and second one to $s$-wave. Modification of the pole contributions in ”primitive” $K$-matrices $^{13}$–$^{14}$ is evident $^2$

$$g_2^2 \rightarrow f_2^2 (W - m_N)^2, \text{ for } s\text{-wave},$$

(21)

$$g_2^2 \rightarrow f_2^2 (W + m_N)^2, \text{ for } p\text{-wave}.$$  

(22)

One can expect that the inclusion of derivatives most strongly affects on threshold properties of $s$-wave due to dumping factor $^3$ $(W - m_N)^2$.

### III. PARTIAL AMPLITUDES OF $\pi N$ SCATTERING

We will use the described above $K$-matrix for description of partial waves $S_{11}$ and $P_{11}$ of $\pi N$ scattering in the energy region $W < 2$ GeV. Following $^3$ we will use three channels of reaction: $\pi N$, $\eta N$ and $\sigma N$, where the last is ”effective” channel, imitating different $\pi \pi N$ states. ”Primitive” $K$-matrices have a form $^{13}$–$^{14}$ but can contain several $J^P = 1/2^+$ and $J^P = 1/2^-$ states.

First of all, let us try to describe $S_{11}$ and $P_{11}$ waves separately. $p$-wave is described rather well by our formulas with derivative in vertex $^{21}$–$^{22}$, see Fig. 1. In this case the $s$-wave states are missing in amplitudes, the $p$-wave $K$-matrix has two positive energy poles.

$^2$ It is not difficult to understand that this rule holds for resonance contribution of any parity $J^P = 1/2^\pm$.

$^3$ As for $J^P = 1/2^-$ baryons, the presence of derivative in vertex leads to contradiction with data near threshold in $S_{11}$ due to factor $(W - m_N)^2$ in $^{21}$, see Fig. 5.
Figure 1: The results of fitting of $P_{11}$-wave of $\pi N$ scattering. Dots show results of PWA [13], solid lines represent our amplitudes (10)–(14) in the presence of derivative in vertex (21)–(22). $K$-matrix has only $p$-wave states. On the right side: $p$-wave inelasticity [15], the curve corresponds to lines on the left side. Partial wave normalization corresponds to [15]: $\text{Im } f = |f|^2 + (1 - \eta^2)/4$.

Best-fit parameters corresponding to Fig. 1 (in GeV units) are:

$$
\begin{align*}
    m_1 &= 1.236 \pm 0.003, \quad g_{1, \pi} = 7.93 \pm 0.07, \quad g_{1, \sigma} = 8.47 \pm 0.11, \quad g_{1, \eta} = -2.90 \pm 0.20, \\
    m_2 &= 1.504 \pm 0.001, \quad g_{2, \pi} = 6.54 \pm 0.05, \quad g_{2, \sigma} = 6.76 \pm 0.06, \quad g_{2, \eta} = 5.0 \text{ (fixed)}, \\
    m_\sigma &= 0.3 \text{ (fixed)}, \quad \chi^2/\text{DOF} = 273/95. 
\end{align*}
$$

The use of vertices without derivative leads to impairment of quality of description: $\chi^2 > 350$, again we need two poles with close masses.

Both variants give a negative background contribution to $S_{11}$ wave, comparable in magnitude with other contributions, as it seen on Fig. 2. Variant without derivative in vertex gives a larger background contribution, rapidly changing near thresholds. Of course, we use rather rough approach – effective $\sigma N$ channel can have different origin in these waves. So, behavior of background contribution at low energy (especially without derivative in vertex) is not well-defined. But it seems that description of $P_{11}$ partial wave without derivative in vertices contradicts to data on $S_{11}$. On Fig. 2 there are shown some typical curves, there exist different variants with sharp behavior near thresholds. The presence of derivative in a vertex suppresses the threshold region in background contribution due to factor $(W - m_N)^2$, but in resonance region this is rather large contribution, see Fig. 2.

Attempt to describe partial wave $S_{11}$ without background contribution has no success: a

---

4 Visible cusps in background contribution appear due to presence of large $p$-wave coupling constants, unnatural for $s$-wave, in this term. This is one of manifestations of OPF-mixing.
Figure 2: Background contribution to $s$-wave, generated by $p$-wave states, i.e. in this case $K$-matrix for $s$-wave (13) has only negative energy poles. Solid lines represent variant with derivative in vertex (corresponding to curves on Fig. 1), dashed lines – variant without derivative in vertex.

minimal variant of $K$-matrix with two positive energy poles don’t allow to reach even qualitative agreement with PWA.

As a next step, let us add the background contribution, arising from $p$-wave states (solid lines on Fig. 1) with fixed parameters (23). One can see from Fig. 3 that quality of description is unsatisfactory in this case but double-peak behavior is arisen in partial wave for the first time. It means that to describe $S_{11}$ wave a background contribution is necessary and its value is close to solid line curves at Fig. 1.

Since the MacDowell symmetry connects two partial waves, it is naturally to perform the joint analysis of $S_{11}$ and $P_{11}$ amplitudes, when resonance states in one wave generate background in other and vice versa. In this case $K$-matrices (13)–(14) have poles with both positive and negative energy: we use two $s$-wave and two $p$-wave poles. This leads to noticeable improvement of description, as it seen from Fig. 4; in this case $\chi^2$/DOF = 850/190.

At last, background contributions can be generated not only by negative energy poles but by other terms. We accounted it by adding to elastic amplitudes $\pi N \rightarrow \pi N$ a smooth contributions of the form:

$$\hat{K}_s^B = A + B(W - m_N)^2, \quad \hat{K}_p^B = A + B(W + m_N)^2,$$

(24)

which do not violate the MacDowell symmetry property. Such terms correspond to pole contributions with large masses in $s$- and $p$-waves. Results of joint description of two waves are depicted at Fig. 5. Note that we have quite good description $\chi^2$/DOF = 584/187 and back-
Figure 3: Results of $s$-wave fitting with fixed parameters for $p$-wave states. Parameters of $p$-wave correspond to curves on Fig. 1. $s$-wave contains two states with $K$-matrix masses 1.55 and 1.75 GeV.

Figure 4: Result of joint fitting of $S_{11}$ and $P_{11}$-waves of $\pi N$ scattering. $K$-matrices have two $s$-wave and two $p$-wave poles. Dashed lines show real and imaginary parts of (unitarized) background contribution. Imaginary part of background for $p$-wave is well below than real one and is not seen at figure.

Ground contribution in $S_{11}$ is close to simplest variant of Fig. 2.

So, the performed joint analysis of $S_{11}$ and $P_{11}$ partial waves demonstrates that OPF-mixing gives rather marked effect in production of $1/2^\pm$ baryons.

In Table I we present the values of pole masses and widths obtained by continuation of our amplitudes to complex $W$ plane. As a whole, we see that our values for $m_p$, $\Gamma_p$ are rather close to previously obtained. The only hint for disagreement is appearance at some sheets of a stable
pole $1/2^+$ with $m_p \approx 1500$ MeV instead of generally accepted mass $m_p \approx 1365$ MeV. But this question as well as distribution of poles over different Riemann sheets should be investigated in more correct multi-channel approach, not with effective $\sigma N$ channel.

| Partial wave, PDG values | This work | Some other works |
|--------------------------|-----------|------------------|
| $S_{11}, 1/2^-$          | (1507, 87) | (1502, 95), (1648, 80) [15] |
| N(1535) (1510, 70)       | (1659, 149) | (1519, 129), (1669, 136) [16] |
| N(1650) (1655, 165)      |           |                  |
| $P_{11}, 1/2^+$          | (1365, 194) | (1359, 162) [15] |
| N(1440) (1365, 190)      | (1500, 160) | (1385, 164) [17] |
|                           |           | (1387, 147) [16] |

Table I: Pole masses and widths ($M_R, \Gamma_R$) extracted from poles position in the complex plane $W$: $W_0 = M_R - i\Gamma_R/2$.

Figure 5: Result of joint fitting of $S_{11}$ and $P_{11}$ waves of $\pi N$ scattering. $K$-matrix has two $s$- and two $p$-waves poles and background of form [24].

**IV. CONCLUSIONS**

In the present paper we investigated the manifestation of OPF-mixing in $\pi N$ partial waves $S_{11}$ and $P_{11}$, where baryons $1/2^{\pm}, I = 1/2$ are produced. We found that the effect of mixing of fermion fields with opposite parity can be readily realized in the framework of $K$-matrix approach. It allows to have simple expressions for amplitudes in the case of any resonance.
states and reaction channels. Note that \( s \)- and \( p \)-wave \( K \)-matrices, \((13)–(14)\), have poles with both positive and negative energy and are related with each other by \( \tilde{K}_p(W) = \tilde{K}_s(-W) \).

The so constructed partial waves possess the well-known MacDowell symmetry that connects two partial waves under substitution \( W \rightarrow -W \). Up to now, this symmetry did not play any role in data analysis since it connects physical and unphysical regions. However, taking OPF-mixing into account, MacDowell symmetry leads to physical consequences: resonance in one partial wave gives rise to background contribution in another and vice versa. This connection between two waves, as in case of \( 3/2^\pm \) resonances \([1]\), works mainly in one direction: it generates large negative background in a wave with lower orbital momentum. So we come to idea of joint analysis of two partial waves and it allows to get an additional information about dynamics in higher \( l \) wave. Such an example can be seen at Fig. 2, where two variants of background in \( S_{11} \) are depicted.

Our main purpose here was to see the effects of OPF-mixing in the amplitudes \( S_{11}, P_{11} \) and to estimate their value. So, following \([14]\), we have used simplified three-channel formalism in which \( \sigma N \) is some quasi-channel, imitating different \( \pi\pi N \) intermediate states. In spite of so rough approach we obtained rather good description of \( S_{11} \) and \( P_{11} \) waves, comparable well with more comprehensive analyses \([18–21]\) with number of channels up to 6. We suppose that OPF-mixing (or MacDowell symmetry) can be taken into account not only in \( K \)-matrix formalism but in framework of more detailed dynamical multi-channel approach.

Note, that obtained pole positions not always coincide with the results of previous analyses. For example, for \( N(1440) \) state we found on most sheets a very stable pole with \( \text{Re}W \approx 1500 \) MeV instead of "standard" value \( \approx 1360 \) MeV, see Table I. After various verifications we suppose that this is result of crudity of used approximation (effective \( \sigma N \) channel). But it is possible that here exists some dependency on details of description and it needs more close investigation.

Summarizing, we found out that effect of a loop OPF-mixing is seen in PWA results as a connection between partial waves \( S_{11} \) and \( P_{11} \). We assume that this connection may be of interest as possibility to obtain additional information about \( P_{11} \) wave and baryons \( 1/2^+ \).

V. BIBLIOGRAPHY

[1] A. Kaloshin, E. Kobeleva, and V. Lomov, Int.J.Mod.Phys. A26, 2307 (2011).
[2] O. Krehl, C. Hanhart, S. Krewald, and J. Speth, Phys.Rev. C62, 025207 (2000).
[3] M. Batinic, I. Slaus, A. Svarc, and B. Nefkens, Phys.Rev. C51, 2310 (1995).
[4] L. Y. Glozman and D. Riska, Phys.Rept. 268, 263 (1996).
[5] S. Capstick and W. Roberts, Prog.Part.Nucl.Phys. 45, S241 (2000).
[6] N. Mathur, Y. Chen, S. Dong, T. Draper, I. Horvath, et al., Phys.Lett. B605, 137 (2005).
[7] M. Dillig and M. Schott, Phys.Rev. C75, 067001 (2007).
[8] A. Sarantsev, M. Fuchs, M. Kotulla, U. Thoma, J. Ahrens, et al., Phys.Lett. B659, 94 (2008).
[9] B. Julia-Diaz and D. Riska, Nucl.Phys. A780, 175 (2006).
[10] C. Roberts, Prog.Part.Nucl.Phys. 61, 50 (2008).
[11] S. W. MacDowell, Phys. Rev. 116, 774 (1959).
[12] R. A. Arndt, J. M. Ford, and L. Roper, Phys.Rev. D32, 1085 (1985).
[13] S. Ceci, A. Svarc, and B. Zauner, Eur.Phys.J. C58, 47 (2008).
[14] S. Ceci, J. Stahov, A. Svarc, S. Watson, and B. Zauner, Phys.Rev. D77, 116007 (2008).
[15] R. Arndt, W. Briscoe, I. Strakovsky, and R. Workman, Phys.Rev. C74, 045205 (2006).
[16] M. Doring, C. Hanhart, F. Huang, S. Krewald, and U.-G. Meissner, Nucl.Phys. A829, 170 (2009).
[17] G. Hohler, πN Newslett. pp. 108–123 (1993).
[18] S. Nakamura, AIP Conf.Proc. 1374, 505 (2011).
[19] H. Kamano, S. Nakamura, T.-S. Lee, and T. Sato, Phys.Rev. C81, 065207 (2010).
[20] B. Golli and S. Sirca, Eur.Phys.J. A38, 271 (2008).
[21] M. W. Paris and R. L. Workman, Phys.Rev. C82, 035202 (2010).