Resonances and Θ-production mechanisms

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After explaining the necessity for exotic hadrons, we discuss mechanisms which could account for the production of the exotic Θ-baryon. A possible important role of resonances (producing the Θ in real or virtual decays) is advanced and emphasized for selected processes. Promising experimental investigations of such resonances, and the Θ itself, are suggested. We also briefly discuss recent negative results regarding the Θ-baryon.

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The problem of observing multiquark (exotic and/or "cryptoexotic") states is as old as quarks themselves. The first experimental results on searches for exotics [1–3] were published soon after the invention of quarks [4,5]. The initial straightforward motivation of "Why not?" was later supported by duality considerations [6] (duality was understood in those times as a correspondence between the sum over resonances and the sum over reggeons). However, several years of experimental uncertainty generated the following question: "Why are there no strongly bound exotic states …, like those of two quarks and two antiquarks or four quarks and one antiquark?" [7].

An attempt to give a reasonable, though model-dependent, answer to this question was made in the confined relativistic quark model (so called MIT bag) [8–10]. The main conclusion was that the multiquark states should exist, and so "… either these states will be found by experimentalists or our confined, quark-gluon theory of hadrons is as yet lacking in some fundamental, dynamical ingredient which will forbid the existence of these states or elevate them to much higher masses" [8].

What is essential is that neither approach based on QCD could change this statement, which, therefore, has become even stronger with time. However, details of the expected properties of exotic hadrons are rather different in different approaches. For instance, the MIT bag prescribes $J^P=1/2^-$ for the lightest baryon with $S=+1$ [9], while the chiral soliton approach (ChSA) predicts $J^P=1/2^+$ (see Refs. [11,12] for recent re-analyses of ChSA predictions and more detailed references). The mass of such a baryon should be either about 1700 MeV, in the MIT bag [9], or, in the ChSA most probably below 1600 MeV [13]. Predicted widths of exotic hadrons differ strongly as well. The MIT bag explains unsuccessful searches for exotic states by their broad widths, of several hundred MeV [8–10], while, according to the ChSA, at least some exotic states may be quite narrow as compared to the familiar resonances [14]. Numerous recent theoretical papers use various theoretical approaches, and yet they could not resolve the ambiguities in the expected properties of the exotic hadrons.

The long-time absence of definite experimental results regarding exotics had practically stopped the corresponding activity, both theoretical and experimental. The Reviews of Particle Properties ceased to touch upon exotics after the issue of 1986 [15]. Nevertheless, the paper of Diakonov, Petrov, and Polyakov [14], that predicted the lightest exotic baryon should have a mass of about 1530 MeV and a width of less than 15 MeV, stimulated new experimental analyses. These provided, at last, positive evidence for the baryon Θ^+ with $S=+1$. Its observation has been reported now in more than 10 publications [16–26], and the measured mass of about 1540 MeV looks similar to expectations of the ChSA.

However, the spin and parity of the Θ are unknown. Furthermore, its indirectly estimated width of order 1 MeV [27–30] seems to be unexpectedly narrow, even for ChSA. Moreover, each of the experiments reporting positive results for the Θ has relatively low statistics (mainly about 40–50 events above the background) which looks insufficient at present. Therefore, even the existence of the Θ^+ requires still more indisputable proof.

Meanwhile, there have appeared some experimental publications which do not see the Θ^+ [31–33]. Really, they do not contradict its existence. Indeed, the restrictions of Ref. [31] are rather weak (see the Appendix for their more detailed discussion), and some features of the data of Ref. [32] still hint at a possibility to extract a Θ^+. Reference [33] gives the best illustration of the present uncertain status: the Conference talk with "a statistically significant peak" for the $\overline{\Theta}^-$ has been transformed into a Proceedings contribution with a "no structure" statement. That is why we will not discuss here other evidence for the Θ-nonobservation, still being at the level of rumors and/or slides (a long list of them is given, e.g., in Ref. [34]). Nevertheless, we do note that searches for the Θ^+ now exploit very different processes, with different initial particles and different energies. Amplitudes and cross sections of these processes may (and should) contain contributions of various quite different mechanisms, and not all of them produce the Θ. Therefore, some procedures to separate the mechanisms may be inevitable, before one can observe the Θ^+, even if it has been produced.

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We wish to emphasize, however, that if the present evidence for the Θ appeared incorrect, it would not make the situation easier, since all the old haunting questions on exotics would be immediately revived. Therefore, we take today a more conservative position, that the Θ does exist, but its production under different conditions is governed by different mechanisms, with a very different intensity. Though we essentially agree with the suggestions of Karliner and Lipkin [34] about how to clarify the problem, we think that, first of all, it is especially important to reliably confirm the existence of the Θ in the processes where it has been reported to be seen. The corresponding new data are being collected and treated just now by several collaborations.

In the present note, we discuss qualitative features of the possible mechanisms for producing the Θ and suggest some lines of investigation to clarify them.

Even the first information on Θ^+ led to attempts to understand how it is produced, and to estimate the production cross section. If, for definiteness, we consider the photoproduction processes,

$$\gamma + n \to K^- + \Theta^+ \tag{1}$$

and/or

$$\gamma + p \to \overline{K^0} + \Theta^+ \tag{2}$$

(and related electroproduction processes, with virtual photons), then the most evident contributions come from exchanges by strange mesons (K and K^*, first of all) in the t-channel, and by baryons (Θ and its possible excitations) in the u-channel. There are also s-channel contributions which correspond, first of all, to formation of various resonances with nonexotic quantum numbers.

All those exchange contributions decrease with increasing energy. To understand this, consider, for example, exchanges by mesons, K and/or K^*. At high energies, they should be reggeized, and their contributions to the amplitudes are $\sim s^{\alpha_i(t)}$, where $\alpha_i(t)$ is the reggeon trajectory, with $i=K$ and/or K^*. Being integrated over scattering angles, such contributions reveal an energy behavior $\sim s^{2\alpha_i(0)-1}$. Known Regge trajectories may be taken, with good accuracy, to be linear,

$$\alpha(t) \approx \alpha(0) + \alpha' t,$$

with $\alpha' \approx 1\ \text{GeV}^{-2}$. Then, for K and K^* exchanges, having $\alpha_K(m_K^2)=0$ and $\alpha_{K^*}(m_{K^*}^2)=1$, we obtain $2\alpha_K(0)-1\approx -1.5$ and $2\alpha_{K^*}(0)-1\approx -0.6$. Therefore, contributions of both meson exchanges, and their interference as well, decrease at high energies. Note, that K^* exchange vanishes somewhat slower (and, therefore, becomes more essential) at high energies, than K exchange. Similar conclusions may be obtained for baryon exchanges, and also for exchange contributions in other reactions of Θ-production.

Thus, exchanges cannot determine the Θ-production at high energies, though they might be essential at some moderate energies. To check such a possibility, we can compare the Θ photoproduction processes to strangeness photoproduction with the usual, nonexotic hadrons in the final state. Take, for example, reactions such as

$$\gamma + N \to K + \Lambda(\Sigma). \tag{3}$$

They are kinematically similar to reactions (1) and (2), and have the same t-channel exchanges. These processes have been studied experimentally by different collaborations [35]. Analyses of the data, up to photon energies E_γ of several GeV, suggest that important contributions come not only from meson or baryon (u-channel) exchanges, but also from various s-channel resonances. Similar conclusions seem to be true as well for the photoproduction of the mesons η [36] and η' (see Ref. [37] and references therein), which contain $s\bar{s}$ pairs.

By analogy, we expect that Θ-photoproduction should also be essentially determined by the contributions of some resonances. What could those resonances be? Up until now, we know only one such candidate, evidenced for by the CLAS Collaboration at JLab [22] and corresponding to a rather narrow peak in the mass distribution of the system $(K^-\Theta^+)$ near 2400 MeV. We will call it $N^*(2400)$.

Note, however, that the measured spectrum [22] may suggest evidence for other peaks as well. Moreover, just as in the cases of the photoproduction of the kaon-hyperon or η, and especially for η'-photoproduction, the resonances contributing to the Θ-photoproduction do not need to be real; they can be virtual, subthreshold or above-threshold. So, even some well-known, rather light nucleon resonances could participate in reactions (1) and (2), even though, because of their low mass, they can decay to $\overline{K}\Theta$ only virtually.

Resonances may be essential also for inclusive Θ-production at high energies. For example, the $N^*(2400)$ (or some its analog) might be produced in diffractive dissociation of the initial nucleon, and then decay to a Θ^+. The corresponding cross section could be nondecreasing (or slowly decreasing) with increasing energy. This does not mean that the cross section would be large. Just the opposite, it will inevitably be small. If the resonance is mainly a 3-quark system, its branching to Θ^+ should be small (we consider the small size of the coupling between the Θ and KN channel to be a general phenomenon). If the resonance is mainly multi-quark, its branching to Θ may be large, but its diffractive production should be suppressed. Thus, the Θ-production at high energies can be nonvanishing, but it may be essentially determined by other mechanisms, and appear smaller, as compared to intermediate energies.

Here we would like to note Ref. [38] which mainly reviews results of the SPHINX Collaboration. Its Figs. 5, 11, and 14a show a small, but rather clear, bump in the spectrum of the diffractive excitation,

$$p \to \Sigma^0 K^+,$$

having just $M=2400$ MeV. The same bump appears to be seen in Fig. 12 for the excitation

$$p \to \Sigma^+ K^0,$$

and in Fig. 14(b) for

$$p \to p\eta.$$

It could be one more independent manifestation of the $N^*(2400)$. If so, its small size could be a confirmation of its (mainly) multi-quark structure.

Since the $N^*(2400)$ is today the only hypothetical resonance directly related to the Θ^+, let us discuss its properties in some detail. The isospin of the $N^*(2400)$ should be $I=1/2$, to allow decay into $\bar{K}\Theta$, with Θ being an isosinglet. Further, the state $N^*(2400)$ was discovered [22] in the reaction

$$\gamma + p \to \pi^+ + K^- + \Theta^+, \ \Theta^+ \to K^+ + n, \tag{4}$$

being seen as an intermediate stage of the cascade,

$$\gamma + p \to \pi^+ + n^*(2400), \ n^*(2400) \to K^- + \Theta^+. \tag{5}$$

The kinematical cuts were applied so as to enhance the contribution of pion exchange. Therefore, the $N^*(2400)$ emerges here as a resonance in the process,

$$\pi^- + p \to K^- + \Theta^+, \tag{6}$$

with a virtual initial pion. This means that the $N^*(2400)$ needs to have nonvanishing coupling to the πN-channel. It should, thus, have the corresponding decay mode, and appear as a resonance in the πN interaction. Of course, such a heavy πN resonance may have such a small elastic branching ratio, so as to make it practically unobservable in elastic πN scattering. In any case, no partial wave analysis of πN scattering data in this mass range has seen an $N^*(2400)$ with a total width of more or about 100 MeV and elasticity of more or about 5% [39].

In this connection, it would be very interesting to study the reaction (6) with a real negative pion. We expect that the process should reveal a rather narrow enhancement at about $T_\pi = 2.45$ GeV. Such investigations would be very interesting for studies of both Θ^+ and πN-resonances.

Let us discuss possible $SU(3)_F$ properties of the $N^*(2400)$. As explained, it should be coupled to both the πN channel (where each particle belongs to the corresponding flavor octet), and the $\bar{K}\Theta$ (one particle from octet and another from antidecuplet). Since (see, e.g., Ref. 40)

$$8 \times 8 = 1 + 8_F + 8_D + 10 + \overline{10} + 27, \ 8 \times \overline{10} = 8 + \overline{10} + 27 + \overline{35}, \tag{7}$$

then, in the case of exact $SU(3)_F$ symmetry, the $N^*(2400)$ should belong to one of the three flavor multiplets: 8, $\overline{10}$, or 27 (of course, the antidecuplet here is not that which contains the Θ^+).

Studies of the $N^*(2400)$, formed in photoproduction (1) and/or (2) as the s-channel resonance at $E_\gamma \approx 2.6$ GeV, could help us to discriminate between these cases. To explain this point, we may use the notion of U-spin [41]. It is analogous to I-spin, that is, to the familiar isospin. But if the I-spin mixes u- and d-quarks, with the s-quark being a singlet, then the U-spin mixes d- and s-quarks, having the same electric charge, with the u-quark being a singlet. Therefore, all members of any U-spin multiplet should have the same electric charge. This implies that if $SU(3)_F$ is exact and the photon interaction with quarks is universal, up to electric charges, the photon is the U-spin singlet, and its absorption cannot change U-spin of any initial hadron.

Now, let us compare "protons" and "neutrons" in different unitary multiplets. The p-like component of every octet (together with Σ^+) belongs to a U-spin doublet, having $U=1/2$. On the other side, the n-like component of the same octet (together with Ξ^0 and a combination of Σ^0 and Λ^0 components) is a member of a U-spin triplet, and has $U=1$. For an antidecuplet, the n-like component also has $U=1$ (together with Σ^0 and Ξ^0), while the p-like component has $U=3/2$ (together with Θ^+, Σ^+, and Ξ^+). The situation for a 27-plet is more complicated: the p-like component (with $I=1/2$) is a superposition of two parts, with $U=1/2$ and 3/2, while the n-like component (also with $I=1/2$) consists of parts with $U=1$ and 2 (compare to the photon, being the U-spin singlet, but having isoscalar and isovector parts).

Note, that the initial hadrons in the reaction (6) have $U(\pi^-)=U(p)=1/2$, and their total U-spin can be either 0 or 1. On the other side, the final hadrons have $U(K^-)=1/2$, $U(\Theta^+)=3/2$, and their admissible U-spin is 1 or 2. Thus, only the U-vector part of the $n^*(2400)$ could contribute to this reaction, if $SU(3)_F$ were exact [even if $n^*(2400)$ is a member of a 27-plet].

Now, if we compare the photoexcitation of $n^*(2400)$ and $p^*(2400)$, correspondingly, on the usual n and p, their relation depends on $SU(3)_F$-properties of the $N^*(2400)$. In particular, if $N^*(2400)$ belongs to an antidecuplet, then photoexcitation of $p^*(2400)$ is forbidden, for exact $SU(3)_F$.

Of course, $SU(3)_F$ is violated. Nevertheless, one can reasonably expect that the photoexcitation of the $N^*(2400)$, being the member of $\overline{10}$, is much larger on the neutron than on the proton. As an example, recall a similar consideration [42] for photoexcitation of the nonstrange partner of the Θ^+ on the neutron and proton, even accounting for $SU(3)_F$-violation.

Interesting information about the nature of the $N^*(2400)$ could come from its excitation (observed through decay to the Θ^+) in electroproduction, i.e., in reactions (1) and (2) with a virtual photon. If the $N^*(2400)$ is mainly a 5-quark state, then its coupling to the mainly 3-quark nucleon should be small at vanishing photon Q^2. However, as we know from DIS-studies, the role of multi-quark configurations inside the nucleon becomes more important at increasing Q^2. This may provide an increasing effective $\gamma^* NN^*(2400)$-coupling, when Q^2 rises from zero. Correspondingly, the electroexcitation of the $N^*(2400)$ may increase with Q^2, at least, in some interval above zero.

There is one more way to study the electromagnetic vertex $\gamma^* NN^*(2400)$. This is to search for the annihilation,

$$e^+e^- \to \bar{N}N^*(2400) + \text{c.c.} \tag{8}$$

This could be done inclusively, in terms of missing mass with respect to the nucleon. A similar search for the N^*, with subsequent decay $N^* \to N\pi$, was recently published by the BES Collaboration [43], but specifically in the peak of the

J/ψ, where only masses below 2160 MeV are kinematically allowed. The state $N^*(2400)$ could be produced in decays of $\psi(2S)$, but with a different, nonelectromagnetic vertex. It would provide, therefore, different information than the reaction (8) in continuum.

Another possibility is to study the exclusive form of the process (8),

$$e^+e^- \to pK_S\bar{n}K^- + \text{c.c.}, \tag{9}$$

accounting for the consequent decays,

$$N^*(2400) \to \Theta^+\bar{K}, \; \Theta^+ \to NK.$$

The final state (9) has also been studied by BES [31], but only in peaks J/ψ and $\psi(2S)$, where the leading contribution is nonelectromagnetic, while the vertex $\gamma^* NN^*(2400)$ appears to be a small correction. It could be essential for e^+e^--annihilation in the continuum, but the present statistics there are small.

In summary, we have reminded the necessity at the present level of understanding the strong interactions, for exotic hadrons, and discussed various mechanisms of Θ-production. We have emphasized, in such processes, a possible special role for resonances as intermediate objects. Production of the Θ in very different processes, e.g., photo- and electroproduction, e^+e^--annihilation, diffractive excitation, and others, may be useful in order to study both the Θ itself, and the related resonances.

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APPENDIX: Θ^+ IN DECAYS OF CHARMONIUM

The BES Collaboration investigated the decays,

$$J/\psi, \psi(2S) \to pK_S\bar{n}K^- + \text{c.c.}, \tag{A1}$$

to search for single and/or double production of the Θ^+. According to their publication [31], a Θ (or $\bar{\Theta}$) was not found at the level of 10^{-5}. Let us examine this in more detail.

The limit obtained for the double Θ-production from the J/ψ is

$$\text{Br}(J/\psi \to \Theta\bar{\Theta} \to K_S pK^-\bar{n} + K_S\bar{p}K^+n) < 1.1 \times 10^{-5}, \tag{A2}$$

while in the $\psi(2S)$-decays,

$$\text{Br}(\psi(2S) \to \Theta\bar{\Theta} \to K_S pK^-\bar{n} + K_S\bar{p}K^+n) < 0.84 \times 10^{-5}. \tag{A3}$$

These limits cannot be directly compared to other known results. However, using the branching ratios,

$$\text{Br}(\Theta \to K^+n) = 1/2, \; \text{Br}(\Theta \to K_S p) = 1/4,$$

one can derive

$$\text{Br}(J/\psi \to \Theta\bar{\Theta}) < 0.44 \times 10^{-4}, \tag{A4}$$

$$\text{Br}(\psi(2S) \to \Theta\bar{\Theta}) < 0.34 \times 10^{-4}, \tag{A5}$$

and compare them to other measured branching ratios. For instance [44],

$$\text{Br}(J/\psi \to \Lambda\bar{\Lambda}) = (13.0 \pm 1.2) \times 10^{-4}.$$

At first sight, the pair $\Theta\bar{\Theta}$ in J/ψ-decays is strongly suppressed in comparison with $\Lambda\bar{\Lambda}$, at least, by the factor <0.034. But really, the essential part of this suppression, 0.15, comes from kinematics (S-wave decay near the threshold: c.m. kinetic energy $M_{J/\psi} - 2M_\Theta \approx 17$ MeV). The dynamical suppression factor is much weaker, <0.23. For decays of the $\psi(2S)$, a similar comparison with [44],

$$\text{Br}(\psi(2S) \to \Lambda\bar{\Lambda}) = (1.81 \pm 0.34) \times 10^{-4},$$

gives an even weaker suppression, <0.19, with the kinematical factor 0.69 and the dynamical suppression <0.27 (compare it to the dynamical factor <0.23 above).

The most stringent restrictions for single Θ-production are

$$\text{Br}(J/\psi \to K_S p\bar{\Theta} \to K_S pK^-\bar{n}) < 1.1 \times 10^{-5}, \tag{A6}$$

for J/ψ decays, and

$$\text{Br}(\psi(2S) \to K_S p\bar{\Theta} \to K_S pK^-\bar{n}) < 0.60 \times 10^{-5}, \tag{A7}$$

for $\psi(2S)$. Again, one should use branching ratios to obtain

$$\text{Br}(J/\psi \to K^0 p\bar{\Theta}) < 0.44 \times 10^{-4}, \tag{A8}$$

$$\text{Br}(\psi(2S) \to K^0 p\bar{\Theta}) < 0.24 \times 10^{-4}. \tag{A9}$$

The first of these limits may be compared to [44],

$$\text{Br}(J/\psi \to K^- p\bar{\Lambda}) = (8.9 \pm 1.6) \times 10^{-4}, \tag{A10}$$

with the suppression factor <0.049. The only appropriate reference value for decays of $\psi(2S)$ might be [44]

$$\text{Br}(\psi(2S) \to \pi^0 p\bar{p}) = (1.4 \pm 0.5) \times 10^{-4}, \tag{A11}$$

which provides the suppression factor <0.029. We see that the total suppression for the single Θ-production in decays of J/ψ and $\psi(2S)$ is nearly the same as for the double Θ-production in decays of J/ψ (recall the factor of 0.034). It is difficult to separate here kinematical and dynamical factors, but one can expect somewhat stronger kinematical suppression in single Θ-decays, because of 3-body phase space.

Thus, data from BES [31] require some suppression in charmonium decays producing one or two Θ-baryon(s). However, they still admit a rather soft dynamical suppression, say, 1/5 in the probability. Meanwhile, because of necessity to produce directly two more quark-antiquark pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise. It could be even stronger than the limits obtained. Thus, the recent result of BES [31] is only a starting point for investigating exotics in e^+e^--annihilation.

[1] R. L. Cool *et al.*, Phys. Rev. Lett. **17**, 102 (1966).
[2] R. J. Abrams *et al.*, Phys. Rev. Lett. **19**, 259 (1967).
[3] J. Tyson *et al.*, Phys. Rev. Lett. **19**, 255 (1967).
[4] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).
[5] G. Zweig, CERN preprints TH-401, TH-412, 1964.
[6] J. Rosner, Phys. Rev. Lett. **21**, 950 (1968).
[7] H. J. Lipkin, Phys. Lett. **45**, 267 (1973).
[8] R. L. Jaffe and K. Johnson, Phys. Lett. **60**, 201 (1976).
[9] R. L. Jaffe, invited talk at the Topical Conference on Baryon Resonances, Oxford, 5–9 July 1976; preprint SLAC-PUB-1774, July 1976; Oxford Top. Conf. 1976, p. 455.
[10] R. L. Jaffe, Phys. Rev. D **15**, 267 (1977).
[11] H. Walliser and V. B. Kopeliovich, Zh. Eksp. Teor. Fiz. **124**, 483 (2003); [JETP **97**, 433 (2003)]; V. B. Kopeliovich, Usp. Fiz. Nauk **174**, 323 (2004) [Phys. Usp. **47**, 309 (2004)].
[12] J. Ellis, M. Karliner, and M. Praszalowicz, J. High Energy Phys. **0405**, 002 (2004).
[13] M. Praszalowicz, in *Proceedings of the Workshop on Skyrmions and Anomalies*, edited by M. Jezabek and M. Praszalowicz (World Scientific, Singapore 1987), p. 112. See also M. Praszalowicz, Phys. Lett. B **575**, 234 (2003).
[14] D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A **359**, 305 (1997).
[15] M. Aguilar-Benitez *et al.*, Phys. Lett. **170**, 289 (1986).
[16] T. Nakano *et al.*, Phys. Rev. Lett. **91**, 012002 (2003).
[17] V. Barmin *et al.*, Yad. Fiz. **66**, 1763 (2003) [Phys. At. Nucl. **66**, 1715 (2003)].
[18] S. Stepanyan *et al.*, Phys. Rev. Lett. **91**, 252001 (2003).
[19] J. Barth *et al.*, Phys. Lett. B **572**, 127 (2003).
[20] V. Koubarovsky and S. Stepanyan, in *Proceedings of Conference on the Intersections of Particle and Nuclear Physics (CIPANP2003)*, New York, NY, USA, 19–24 May 2003, AIP Conf. Proc. **698**, 543 (2003).
[21] A. Asratyan, A. Dolgolenko, and M. Kubantsev, Yad. Fiz. **67**, 704 (2004) [Phys. At. Nucl. **67**, 682 (2004)].
[22] V. Kubarovsky *et al.*, Phys. Rev. Lett. **92**, 032001 (2004).
[23] A. Airapetian *et al.*, Phys. Lett. B **585**, 213 (2004).
[24] A. Aleev *et al.*, hep-ex/0401024.
[25] M. Abdel-Bary *et al.*, Phys. Lett. B **595**, 127 (2004).
[26] S. Chekanov *et al.*, Phys. Lett. B **591**, 7 (2004).
[27] S. Nussinov, hep-ph/0307357.
[28] R. A. Arndt, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **68**, 042201 (2003); R. A. Arndt, I. I. Strakovsky, and R. L. Workman, nucl-th/0311030.
[29] J. Haidenbauer and G. Krein, Phys. Rev. C **68**, 052201 (2003).
[30] R. N. Cahn and G. H. Trilling, Phys. Rev. D **69**, 011501 (2004).
[31] J. Z. Bai *et al.*, Phys. Rev. D **70**, 012004 (2004).
[32] K. T. Knoepfle, M. Zavertyaev, and T. Zivko, J. Phys. G **30**, 1363 (2004).
[33] C. Pinkenburg *et al.*, J. Phys. G **30**, 1201 (2004).
[34] M. Karliner and H. Lipkin, Phys. Lett. B **597**, 309 (2004).
[35] S. P. Barrow *et al.*, Phys. Rev. C **64**, 044601 (2001). D. S. Carman *et al.*, Phys. Rev. Lett. **90**, 131804 (2003); K.-H. Glander *et al.*, **19**, 251 (2004); J. W. C. McNabb *et al.*, Phys. Rev. C **69**, 042201 (2004).
[36] R. Thompson *et al.*, Phys. Rev. Lett. **86**, 1702 (2001). F. Renar *et al.*, Phys. Lett. B **528**, 215 (2002). M. Dugger *et al.*, Phys. Rev. Lett. **89**, 222002 (2002). V. Credé *et al.*, hep-ex/0311045.
[37] R. Nakayama and H. Haberzettl, Phys. Rev. C **69**, 065212 (2004).
[38] L. G. Landsberg, Phys. Rep. **320**, 223 (1999).
[39] G. Höhler, *Pion-Nucleon Scattering*, Landoldt-Börnstein edited by H. Schopper (Springer-Verlag, Berlin 1983), Vol. I/9b2.
[40] J. J. de Swart, Rev. Mod. Phys. **35**, 916 (1963).
[41] S. Meshkov, C. A. Levinson, and H. Lipkin, Phys. Rev. Lett. **10**, 361 (1963).
[42] M. V. Polyakov and A. Rathke, Eur. Phys. J. A **18**, 691 (2003).
[43] M. Ablikim *et al.*, hep-ex/0405030.
[44] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).