Pis'ma v ZhETF, vol. 94, iss. 7, pp. 543 – 547

On narrow nucleon excitation N*(1685)

V. Kuznetsov[+], *M. V. Polyakov*[○*], *M. Thürmann*[*]

[+]*Institute for Nuclear Research, 117312 Moscow, Russia*

[○]*Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

[*]*St. Petersburg Institute for Nuclear Physics, 188300 St. Petersburg, Russia*

Submitted 16 August 2011

We perform estimates on putative narrow nucleon N*(1685) – the candidate for the non-strange member of the exotic anti-decuplet of baryons. In particular, we consider the recent high precision data on η photoproduction off free proton obtained by the Crystal Ball Collaboration at MAMI. We show that it is difficult to describe peculiarities of these new data in the invariant energy interval of $W \sim 1650-1750$ MeV in terms of known wide resonances. Using very simple estimates, we show that the data may indicate an existence of a narrow N*(1685) with small photocoupling to the proton.

The prediction of light and narrow anti-decuplet of baryons in the framework of the chiral quark soliton model (χQSM) [1] has a direct implication for the classical field of nucleon resonances spectroscopy: one should expect an existence of the nucleon state, which is much narrower than the usual nucleon excitations with analogous mass [1–4].

As pointed out in Ref. [5], the nucleon resonance from the anti-decuplet has a clear imprint of its exotic nature: it is excited by the photon predominantly from the neutron, its photoexcitation from the proton target is strongly suppressed. Therefore the $\gamma n \to \eta n$ process has been suggested in Ref. [5] as a "golden channel" to search for the anti-decuplet nucleon. A modified partial wave analysis (PWA) of the elastic πN scattering [3] showed that the existing data on πN scattering can tolerate a narrow P_{11} resonance at a mass around 1680 MeV if its πN partial decay width is below 0.5 MeV. Such a suppression of the πN decay channel is predicted in χQSM [1, 3, 4].

The pioneering observation in Refs. [6, 7] of a narrow structure in the η photoproduction cross section on the neutron at $W \sim 1680$ MeV (neutron anomaly[1)]) was confirmed by three other groups CBELSA/TAPS [8, 9], LNS [10], and Crystal Ball/TAPS [11].

In Refs. [7, 12–16] the experimental findings were interpreted as a signal of a nucleon resonance with the mass near $\sim$ 1680 MeV and unusual properties: the narrow width and the stronger photoexcitation on the neutron comparing to that on the proton. Alternatively, the authors of Refs. [18, 17] explained the neutron anomaly in terms of the interference of well-known resonances and in Ref. [19] due to effects of meson loops. It is worth noting here that the models of Refs. [18, 17, 19] do not predict the neutron anomaly. The experimental data of Ref. [8] on the peak in the neutron cross-section (and its apparent absence in the proton channel) has been used in these models as an input for fitting of quite numerous model parameters.

In year 2011 more results on the neutron anomaly were obtained.

- In Ref. [20] the neutron anomaly was also observed in the Compton scattering – in this reference the study of quasi-free Compton scattering on the neutron in the energy range of $E_\gamma = 750-1500$ MeV revealed a narrow ($\Gamma = 30 \pm 10$ MeV) peak at $W \sim 1685$ MeV. Such peak is absent in the Compton scattering on the proton.

  We note that the explanations of the neutron anomaly in the η photoproduction in terms of the interference of well-known resonances [18, 17] and due to effects of meson loops [19] obviously do not work in the case of the Compton scattering.

- Recently the data of the CBELSA/TAPS collaboration [8] on η photoproduction off the neutron have been reanalysed by the same collaboration. Namely, the de-folding of the Fermi motion has been performed [9]. As the result the data exhibit pronounced narrow ($\Gamma = 25 \pm 10$ MeV) peak at $W \sim 1670$ MeV. One can use the results of this new analysis in order to extract the photocoupling of neutral component of N*(1685). The method is described in Ref. [14], following it one can easily obtain:

[1)]The name "neutron anomaly" was introduced in Ref. [13] to denote the bump in the quasi-free $\gamma n \to \eta n$ cross section around $W \sim 1680$ MeV and its apparent absence in the quasi-free $\gamma p \to \eta p$ cross section.

$$\sqrt{\mathrm{Br}_{\eta N}} A^n_{1/2} \sim 15 \cdot 10^{-3}\ \mathrm{GeV}^{-1/2}. \qquad (1)$$

That value of the photocoupling is in a striking agreement with the value obtained in Ref. [14] from the analysis of the GRAAL-data of Refs. [6, 7].

It was predicted that the photoexcitation of the charge component of the anti-decuplet nucleon is strongly suppressed [5]. That makes its search more sophisticated. In Refs. [12, 13] it was found that the beam asymmetry for the η photoproduction on the free proton exhibits a narrow structure around $W \sim 1685$ MeV, which looks like a peak at forward angles and which develops into an oscillating structure at larger scattering angles. Such behaviour is typical for interference effects of a narrow resonance with smooth background. Fits to the data provided a rough estimate of the photocoupling for the charge component of N*(1685) [12, 13]:

$$\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} \sim (0.5\text{–}2.5) \cdot 10^{-3}\ \mathrm{GeV}^{-1/2}, \qquad (2)$$

which is much smaller than the couplng to the neutron (1).

Photocouplings (1) and (2) correspond to the following resonance cross section at its maximum (the estimate for the proton channel corresponds to $\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} = 1 \cdot 10^{-3}\ \mathrm{GeV}^{-1/2}$):

$$\begin{aligned} \sigma_{\mathrm{res}}(\gamma n \to \eta n)|_{W=M_R} &\sim 8.5 \left(\frac{10\ \mathrm{MeV}}{\Gamma_{\mathrm{tot}}}\right)\ \mu\mathrm{b}, \\ \sigma_{\mathrm{res}}(\gamma p \to \eta p)|_{W=M_R} &\sim 0.04 \left(\frac{10\ \mathrm{MeV}}{\Gamma_{\mathrm{tot}}}\right)\ \mu\mathrm{b}. \end{aligned} \qquad (3)$$

Typical values of the non-resonant cross section at $W \sim \sim 1680$ MeV is $\sigma_n \sim 5\text{–}6\ \mu$b for the neutron and $\sigma_p \sim 3\ \mu$b for the proton. One sees from that rough estimate that the resonance cross section on the proton is very small and even in a measurement with an ideal resolution it is almost impossible to see the corresponding resonance signal. The signal of weak resonance can be revealed through its quantum interference with the strong but smooth background amplitude, see e.g. [21, 22]. In the case of interference a weak signal can appear not necessarily as a resonance bump but as a dip or a structure oscillating with energy. The *maximally possible* magnitude of such structure can be estimated as:

$$\Delta\sigma_{\mathrm{tot}} = 2\sqrt{\sigma_p\ \sigma_{\mathrm{res}}(\gamma p \to \eta p)|_{W=M_R}} \sim 0.7\ \mu\mathrm{b}, \qquad (4)$$

that number corresponds to $\sim 0.06\ \mu$b/sr in the differential cross section. Note that the actual magnitude of the interference structure must be smaller than the above value, as the estimate (4) assumes that only one partial wave with quantum numbers of the putative resonance contributes to the cross section.

Recently the Crystal Ball Collaboration at MAMI published high precision data on η photoproduction on free proton [23]. The cross section was measured with fine steps in the photon energy. The authors of Ref. [23] concluded that "... cross sections for the free proton show no evidence of enhancement in the region $W \sim 1680$ MeV, contrary to recent equivalent measurements on the quasifree neutron. However, this does not exclude the existence of an N*(1680) state...". As we discussed above one should expect that the putative N*(1685) can be seen in the cross section only due to its interference with strong smooth background and the corresponding signal is not necessarily looks like a peak but rather as the structure oscillating with energy or as a dip.

Let us look more carefully at the energy behaviour of the total cross section in the energy region around $W \sim 1685$ MeV. The data of Ref. [23] for the total cross section of $\gamma p \to \eta p$ for W in the interval 1650–1750 MeV are shown in Fig. 1. One sees clearly an oscil-

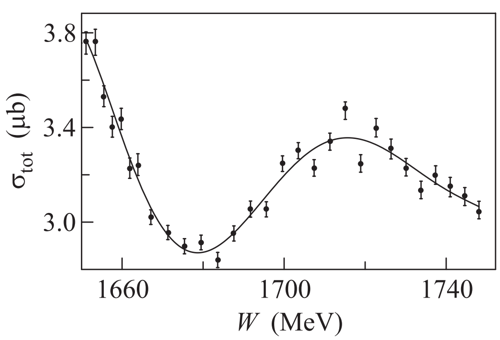

Fig. 1. Total cross section of $\gamma p \to \eta p$ process. The data points are from Ref. [23]. Solid line is the 6th order polynomial fit to the experimental points just to guide the eye

lation structure with the distance between two extrema of $\Delta W \sim 40$ MeV (a minimum at $W \sim 1680$ MeV and a maximum at $W \sim 1720$ MeV). The amplitude of that oscillation structure (the difference between the values of the cross section at the extrema) is about $\sim 0.5\ \mu$b (cf. our estimate (4)). We see that in the invariant energy region 1680–1720 MeV the total cross section of $\gamma p \to \eta p$ reveals a narrow oscillation (or maybe dip) structure with the magnitude compatible with our expectations (4) for the interference pattern of the narrow N*(1685). The amplitude of the oscillation structure and its width are too close to the upper limits what one can expect for the putative narrow resonance N*(1685). It seems that sev-

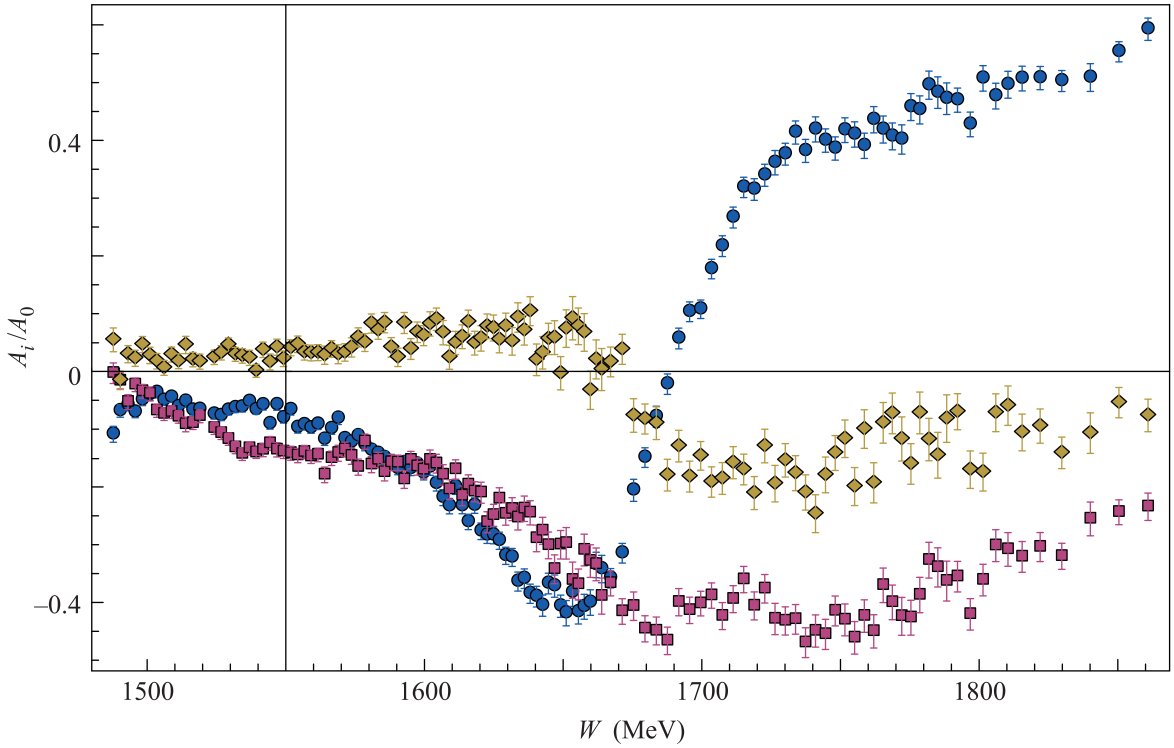

Fig. 2. Coefficients A_i of the Legendre expansion (5) normalized to the total cross section A_0. The coefficients A_i are calculated using the data of Ref. [23]. The filled circles correspond to A_1/A_0, filled squares to A_2/A_0 and filled diamods to A_3/A_0

eral partial waves are in play. It might be that the wide resonances in the neighbourhood of $W \sim 1685$ MeV, such as $P_{11}(1710)$, $P_{13}(1720)$ and $D_{15}(1675)$ can contribute additionally to the enhancement of the observed oscillation. All these contributions can be disentangled by PWA.

The consideration above shows that around $W \sim \sim 1680$ MeV there exists a phenomenon with the typical energy scale of about 20–40 MeV. In order to investigate a possible origin of the phenomenon let us consider the differential cross section. It is convenient to expand the differential cross section in the Legendre series:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \sum_{l=0}^{\infty} A_l(W)\ P_l(\cos\theta), \qquad (5)$$

where P_l are Legendre polynomials.

In Fig. 2 we show the normalized Legendre coefficients (5) (A_i/A_0) extracted from the data of Ref. [23]. One sees that A_1 coefficient undergoes rapid change of its sign on the invariant energy interval of $W \sim \sim 1650-1730$ MeV. Also A_3 changes its sign on that interval, whereas the coefficient A_2 shows little structure on that energy interval. We note that the rapid change of A_1 coefficient occurs exactly at invariant energy, where the rapid change of photon beam asymmetry was observed in Refs. [12, 13].

It is clear that the rapid change of the sign of A_1 can be driven by the interference of various partial waves. Thus one definitely needs sizable values of P and/or D waves in the invariant energy interval of $W \sim 1650-1750$ MeV. That simple observation casts serious doubts on the model of Ref. [19], which predicts the dominance of S-wave in that energy interval.

The main distinctive feature of putative N*(1685) is its small width, one may try to single out its contribution to A_1 considering derivatives dA_1/dW. Indeed, looking at Fig. 2 one might see that the speed of A_1's change with W has probably a qualitatively different regime on narrow energy interval of $W \sim 1670-1700$ MeV. That observation invites us to study the "speed characteristic" of the normalized A_1:

$$S_1(W) \equiv W \frac{d}{dW} \left[\frac{A_1(W)}{A_0(W)}\right]. \qquad (6)$$

That quantity is dimesionless, it allows us to separate rapidly changing contributions from contributions of wide resonances and smooth background. It is difficult to extract $S_1(W)$ from the data because of statistical fluctuations in the data that induce large instabilities in the calculations of the derivative. We use the following procedure to compute $S_1(W)$: for each ith bin in W we choose the energy interval $[W_i, W_{i+12}]$ (about 30 MeV wide) and fit the data by the 4th order polynomial (13 data points). After that, using resulting from the fit polynomial, we compute $S_1(W)$ analytically for the 4 middle bins in the interval $[W_i, W_{i+12}]$. Obviously, the resulting value of $S_1(W)$ for a given W depends on the initial bin in our procedure. The differences of values of $S_1(W)$ reflect the uncertainties in differentiation of the numerical data.

In Fig. 3 we plot $S_1(W)$ obtained by that procedure. We see that at W around 1660 MeV and 1690 MeV the

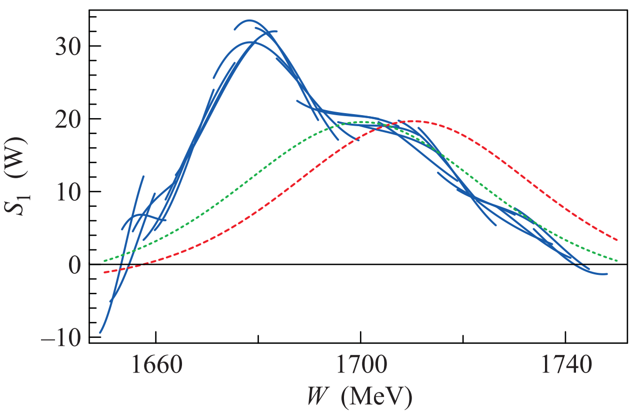

Fig. 3. Extracted values of $S_1(W)$ (6) on the energy interval of 1650–1750 MeV. As an example, we show by the dashed line the contribution of 100 MeV wide P_{11} resonance with the mass of 1710 MeV (dotted line corresponds to $M_R = 1700$ MeV) and $\sqrt{\mathrm{Br}_{\eta N}}A^p_{1/2} \sim 8\cdot 10^{-3}$ GeV$^{-1/2}$ (that corresponds to $\sigma_{\mathrm{res}}/\sigma_{\mathrm{tot}} \sim 0.1$). The values of the mass and width are chosen in accordance with the central values for those parameters provided by the Particle Data Group [24] for the three star N(1710) resonance

"speed characteristic" $S_1(W)$ (6) is very uncertain (one obtains very different values depending on the starting bin), whereas between these points the $S_1(W)$ is rather stable. That means that at points 1660 and 1690 MeV the change of the regime of the W dependence of the normalized A_1 happens. Also it is remarkable that $S_1(W)$ reaches its maximum at $W \sim 1680$ MeV (that is corresponds to the inflection point of the normalized A_1) which is close to zero of $A_1(W)$ at $W \sim 1685$ MeV. Such situation is typical for the case when A_1 appears as the result of interference of two partial waves: one is smooth (say S-wave) and another is dominated by a resonance (say P-wave). Note that the value of $S_1(W)$ at maximum at 1680 MeV is rather sizable: $S_1^{\max} \sim 30$.

If one uses a simple model, which consist of smooth S_{11} amplitude and a narrow P_{11} resonance (mass M_R and total width Γ_R) on the top of smooth background one can derive a simple expression for $S_1^{\max}$:

$$S_1^{\max} = 4\frac{M_R}{\Gamma_R}\sqrt{\frac{\sigma_{\mathrm{res}}}{\sigma_{\mathrm{tot}}}}\sqrt{1-r}\,(1-2r), \qquad (7)$$

where r is the fraction of the P_{11} partial wave in σ_{tot} at $W = M_R$ and σ_{res} is the resonance cross section. We note that this equation is derived under the assumptions that the resonance is weak, i.e. $\sigma_{\mathrm{res}} \ll \sigma_{\mathrm{tot}}$. We consider this limit because otherwise (for $\sigma_{\mathrm{res}} \sim \sigma_{\mathrm{tot}}$) the resonance should be seen in the total cross section as a clean cut peak.

From Eq. (7) one obtains that for the known wide resonances of width $\Gamma_R \sim 100$–200 MeV $S_1^{\max} \le \le (22$–$11)$ even for optimistically large cross section ratio of $\sigma_{\mathrm{res}}/\sigma_{\mathrm{tot}} = 0.1$. As an illustration, the contribution of $P_{11}(1710)$ resonance to $S_1(W)$ is shown by the dashed line in Fig. 3. For the calculations we used the central values of the N(1710) parameters listed by the Particle Data Group [24]: $M_R = 1710$ MeV, $\Gamma_R = 100$ MeV whereas for the photocoupling we took $\sqrt{\mathrm{Br}_{\eta N}}A^p_{1/2} \sim 8\cdot 10^{-3}$ GeV$^{-1/2}$ which corresponds to the maximal value provided by PDG. The latter value corresponds to $\sigma_{\mathrm{res}}/\sigma_{\mathrm{tot}} \sim 0.1$, if one uses the central values of N(1710) parameters listed by PDG one obtains the contribution to $S_1(W)$ which is about 10 times smaller than the one shown by the dashed line on Fig. 3.

One sees that it is very difficult to obtain the experimental value of $S_1^{\max} \sim 30$ by contribution of known wide resonances if the corresponding resonance cross section is not large. For the case of the large resonance cross section the corresponding resonance should be visible as a peak in the differential cross section.

According to Eq. (7), another possibility to obtain the large experimental value of $S_1^{\max} \sim 30$ is due to the contribution of a narrow resonance with small photocoupling to the proton (small ratio of cross sections $\sigma_{\mathrm{res}}/\sigma_{\mathrm{tot}}$). From Eq. (7) we see that for each value of parameter r we can determine a relation between $\sqrt{\mathrm{Br}_{\eta N}}A^p_{1/2}$ and the resonance total width Γ_R. Taking experimental values of $\sigma_{\mathrm{tot}} \sim 3\mu$b and $S_1^{\max} \sim 30$ we plot in Fig. 4 the relation between $\sqrt{\mathrm{Br}_{\eta N}}A^p_{1/2}$ and the resonance width for several values of the parameter r. Also we plot our estimation of $\sqrt{\mathrm{Br}_{\eta N}}A^p_{1/2}$ (2) obtained from the analysis of the beam asymmetry in η photoproduction off free proton [12, 13].

Given that our estimates are very rough, the agreement is rather impressive. We can conclude from the presented simple analysis that the observed in Ref. [23] oscillation of $\sigma_{\mathrm{tot}}(\gamma p \to \eta p)$ and rapid change of the Legendre coefficient $A_1(W)$ around $W \sim 1685$ MeV may indicate an existence of new narrow N*(1685) resonance

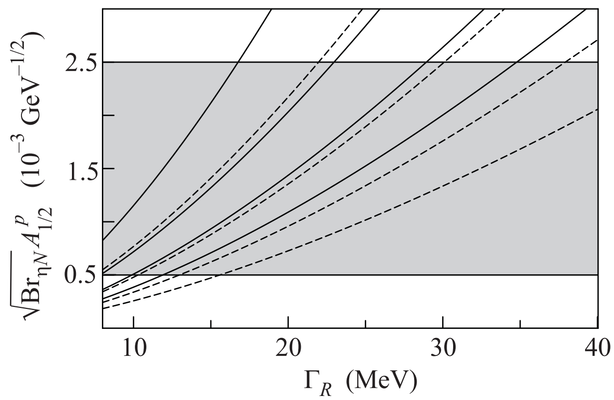

Fig. 4. Lines show the relation between $\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2}$ and the width of putative resonance Γ_R obtained from Eq. (7) with the experimental input $S_1^{\max} \sim 30$ and $\sigma_{\mathrm{tot}} \sim 3$ μb. The lines correspond to values of the parameter $r = 0, 0.1, 0.2$ and 0.3 (the larger r the steeper the curve). Shaded area shows our estimate given by Eq. (2). By dashed lines we show the solutions of Eq. (7) for the case of $S_1^{\max} \sim 20$

with $\Gamma_{\mathrm{tot}} \leq 50$ MeV and small resonance photocoupling in the range of $\sqrt{\mathrm{Br}_{\eta N}} A^p_{1/2} \sim (0.3\text{–}3) \cdot 10^{-3}$ GeV$^{-1/2}$. These parameters are in agreement with the analysis of the photon beam asymmetry in $\gamma p \to \eta p$ process performed in Refs. [12, 13].

The estimates presented here provide us the feeling of the expected scales for the effect of putative N*(1685) in the cross section of $\gamma p \to \eta p$. The estimates also show that the effect of putative N*(1685) is interlaced with effects of neighbourhood wide resonances, such as $P_{11}(1710)$, $P_{13}(1720)$ and $D_{15}(1675)$. We hope that our simple estimates were able to grasp main physics in observed phenomena and future PWA will be able to detail our observations.

It seems that all experimental facts discussed here strongly support the existence of new narrow nucleon excitation N*(1685) with properties neatly coinciding with those predicted for the non-strange member of exotic anti-decuplet [1–5] (for the most recent analysis of the properties of anti- decuplet baryons see Ref. [25]).

This work has been supported by SFB/Transregio 16 (Germany). We are thankful to M. Döring, A. Fix, A. Sarantsev, and L. Tiator for interesting discussions and for correspondance.

1. D. Diakonov, V. Petrov, and M. V. Polyakov, Z. Phys. A **359**, 305 (1997) [arXiv:hep-ph/9703373].
2. D. Diakonov and V. Petrov, Phys. Rev. D **69**, 094011(2004) [arXiv:hep-ph/0310212].
3. R. A. Arndt et al., Phys. Rev. C **69**, 035208 (2004) [arXiv:nucl-th/0312126].
4. J. R. Ellis, M. Karliner, and M. Praszalowicz, JHEP **0405**, 002(2004) [arXiv:hep-ph/0401127]; M. Praszalowicz, Acta Phys. Polon. B **35**, 1625(2004) [arXiv:hep-ph/0402038].
5. M. V. Polyakov and A. Rathke, Eur. Phys. J. A **18**, 691 (2003) [arXiv:hep-ph/0303138].
6. V. Kuznetsov [GRAAL Collaboration], arXiv:hep-ex/0409032.
7. V. Kuznetsov et al., Phys. Lett. B **647**, 23 (2007) [arXiv:hep-ex/0606065].
8. I. Jaegle et al. [CBELSA Collaboration and TAPS Collaboration], Phys. Rev. Lett. **100**, 252002 (2008) [arXiv:0804.4841 [nucl-ex]].
9. I. Jaegle et al., Eur. Phys. J. A **47**, 89(2011) [arXiv:1107.2046 [nucl-ex]].
10. F. Miyahara et al., Prog. Theor. Phys. Suppl. **168**, 90 (2007).
11. D. Werthmuller [for the Crystal Ball/TAPS collaborations], Chin. Phys. C **33**, 1345 (2009) [arXiv:1001.3840 [nucl-ex]].
12. V. Kuznetsov et al., Acta Phys. Polon. B **39**, 1949 (2008) [arXiv:0807.2316 [hep-ex]]; V. Kuznetsov et al., arXiv:hep-ex/0703003.
13. V. Kuznetsov and M. V. Polyakov, JETP Lett. **88**, 347 (2008) [arXiv:0807.3217 [hep-ph]].
14. Y. I. Azimov et al., Eur. Phys. J. A **25**, 325 (2005) [arXiv:hep-ph/0506236].
15. K. S. Choi, S. I. Nam, A. Hosaka, and H. C. Kim, Phys. Lett. B **636**, 253 (2006) [arXiv:hep-ph/0512136].
16. A. Fix, L. Tiator, and M. V. Polyakov, Eur. Phys. J. A **32**, 311 (2007) [arXiv:nucl-th/0702034].
17. V. Shklyar, H. Lenske, and U. Mosel, Phys. Lett. B **650**, 172 (2007) [arXiv:nucl-th/0611036].
18. A. V. Anisovich et al., Eur. Phys. J. A **41**, 13 (2009) [arXiv:0809.3340 [hep-ph]].
19. M. Doring and K. Nakayama, Phys. Lett. B **683**, 145 (2010) [arXiv:0909.3538 [nucl-th]].
20. V. Kuznetsov et al., Phys. Rev. C **83**, 022201(R) (2011) [arXiv:1003.4585 [hep-ex]].
21. M. Amarian, D. Diakonov, and M. V. Polyakov, Phys. Rev. D **78** (2008) 074003 [arXiv:hep-ph/0612150].
22. Y. Azimov, J. Phys. G **37** (2010) 023001 [arXiv:0904.1376 [hep-ph]].
23. E. F. McNicoll et al. [Crystal Ball Collaboration at MAMI], Phys. Rev. C **82**, 035208(2010) [arXiv:1007.0777 [nucl-ex]].
24. K. Nakamura *et al.* [Particle Data Group], J. Phys. G **37** (2010) 075021.
25. K. Goeke, M. V. Polyakov, and M. Praszalowicz, Acta Phys. Polon. B **42**, 61 (2011) [arXiv:0912.0469 [hep-ph]]; M. Praszalowicz, Acta Phys. Polon. Supp. **3**, 917(2010) [arXiv:1005.1007 [hep-ph]].