THE EUROPEAN
PHYSICAL JOURNAL A

Letter

Primakoff effect in η-photoproduction off protons

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Abstract. We analyse data on forward η-meson photoproduction off a proton target and extract the $\eta\rightarrow\gamma\gamma$ decay width utilizing the Primakoff effect. The hadronic amplitude that enters into our analysis is strongly constrained because it is fixed from a global fit to available $\gamma p \to p\eta$ data for differential cross-sections and polarizations. We compare our results with present information on the two-photon η-decay from the literature. We provide predictions for future PrimEx experiments at Jefferson Laboratory in order to motivate further studies.

The decay of the light pseudoscalar mesons into two photons is related to symmetry breaking through the axial vector anomaly and reveals one of the fundamental properties of QCD [1–8]. The Adler-Bell-Jackiw (ABJ) anomaly [1,2] allows to determine the decay constant of those pseudoscalar mesons from the two-photon decay width (invoking a smooth extrapolation from the chiral limit to the physical light quark masses). While this is indeed feasible for the π^0-meson, the situation is more complicated for the η-meson since the extrapolation from the η-mass to zero and the dominance of the ABJ anomaly is debatable. Moreover, for the η and η' mesons the decay constants [9] alone do not determine the two-photon decay widths uniquely. It is necessary to know in addition the singlet-octet mixing angle.

In an extension of chiral perturbation theory including the η' meson —from now on called the Extended Effective Theory (EET)— the evaluation of the $\eta \to \gamma\gamma$ decay width requires a proper mixing of the $SU(3)$ pseudoscalar singlet and octet states so that [10]

$$\Gamma(\eta \to \gamma\gamma) = \frac{\alpha^2 m_\eta^3}{96\pi^3} \left[\frac{\cos\theta_P}{f_\eta^8} - \frac{\sqrt{8}\sin\theta_P}{f_\eta^0} \right]^2. \quad (1)$$

Here, f_η^0 and f_η^8 are the singlet and octet decay constants, θ_P is the mixing angle, and α is the fine structure constant. To estimate the $\eta \to \gamma\gamma$ radiative decay width we take from ref. [11] the following set of $SU(3)$ parameters: $f_\eta^0 = (1.17 \pm 0.03)f_{\pi^0}$, $f_\eta^8 = (1.26 \pm 0.04)f_{\pi^0}$ and

$\theta_P = -(21.2^0 \pm 1.6^0)$. The pion decay constant has the value $f_{\pi^0} = 130 \pm 5\,\text{MeV}$ and the η-meson mass is given by the PDG [12] as $m_\eta = 547.853 \pm 0.024\,\text{MeV}$. With these parameters the $\eta \to \gamma\gamma$ decay width can be estimated to be

$$0.39 \leq \Gamma(\eta \to \gamma\gamma) \leq 0.52\,\text{keV}. \quad (2)$$

Alternatively, assuming that $f_\eta^0 = f_\eta^8 = f_{\pi^0}$ one can, in principle, extract the $SU(3)$ mixing angle from the $\eta \to \gamma\gamma$ decay width [10].

Experimentally, the $\eta \to \gamma\gamma$ decay width was determined through the QED process $e^+e^- \to e^+e^-\eta$ and also from measurements of the Primakoff effect with nuclear targets. The results from these two classes of experiments are in conflict [12]. While all of the QED results [13–18] are in line with eq. (2) within the experimental error, the Primakoff measurements [19,20] agree with the EET only within three times the experimental error bars, say. It was argued [21] that most of the uncertainties in the evaluation from the Primakoff effect are due to the nuclear response. Recently, it was shown [22] that the $\eta \to \gamma\gamma$ results might depend significantly on contributions from incoherent η-meson photoproduction off nuclei.

The Primakoff measurements [23] on a proton target are not included in the list of the PDG [12,21], although the quality of these data, collected at DESY, is comparable or even better than the results obtained with nuclear targets [19,20]. These data were considered [24] as a strong motivation for further $\eta \to \gamma\gamma$ Primakoff studies [25] at JLab, however, so far they were not used explicitly for an extraction of the two-photon decay width.

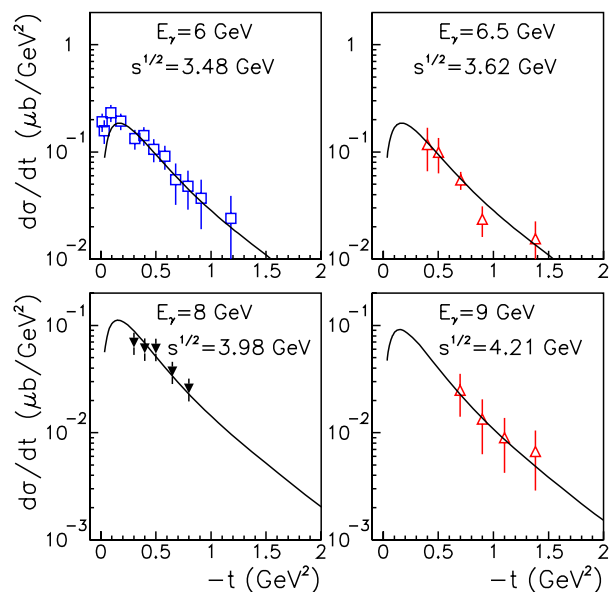[a] e-mail: meissner@hiskp.uni-bonn.de
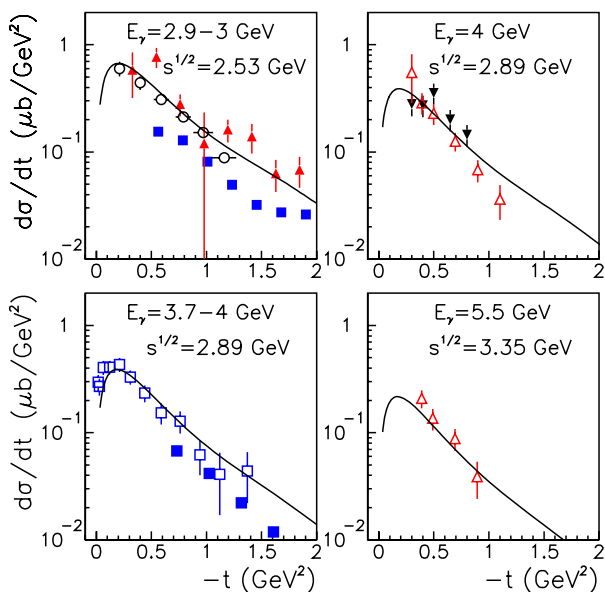
Fig. 1. Differential cross-section for the reaction $\gamma p \rightarrow p\eta$ as a function of the four-momentum transfer squared at different photon energies E_γ or invariant collision energies $\sqrt{s}$. Data are from ELSA-Bonn [29] (filled triangles), the Daresbury Electron Synchrotron [30] (open circles), Cornell [26] (inverse triangles), DESY [23] (open squares), SLAC [31] (open triangles), and CLAS at JLab [32] (filled squares). The lines are the results of our model calculation.

Fig. 2. Differential cross-section for the reaction $\gamma p \rightarrow p\eta$ as a function of the four-momentum transfer squared at different photon energies E_γ or invariant collision energies $\sqrt{s}$. Data are from Cornell [26] (inverse triangles), DESY [23] (open squares) and SLAC [31] (open triangles). The lines are the results of our model calculation.

In the present paper we utilize the data [23,26] available for forward η-meson production in the $\gamma p \rightarrow p\eta$ reaction at photon energies of 4 GeV and 6 GeV in order to extract the $\eta \rightarrow \gamma\gamma$ decay width. To isolate the Primakoff effect from the hadronic contribution we use the Regge amplitudes established in our previous study [27] of the $\gamma p \rightarrow p\pi^0$ reaction. The free parameters of the helicity amplitudes, namely coupling constants and form factors, were fixed by a global fit to η-photoproduction data. In the present study we compare our results to some $\gamma p \rightarrow p\eta$ data on differential cross-sections and polarization available at high energies. A more thorough comparison to experimental results and predictions at photon energies below 3 GeV, together with more detailed information on the used model parameters, will be given elsewhere [28].

Figure 1 shows $\gamma p \rightarrow p\eta$ differential cross-sections at photon energies from 3 GeV to 5.5 GeV. The different measurements available at the same energy are in good agreement with each other, considering their uncertainties, apart from the recent CLAS results [32]. Actually, there are systematic discrepancies between the ELSA-Bonn data published in 2005 [29], in 2008 [33] and in 2009 [34], and the 2009 data from CLAS [32]. A detailed discussion of these discrepancies will be given in ref. [28].

Differential cross-sections for η-photoproduction at energies from 6 to 9 GeV are displayed in fig. 2. The data from the different measurements are described rather well by our model calculation.

Data for beam and target asymmetries are presented in fig. 3 as a function of the four-momentum transfer
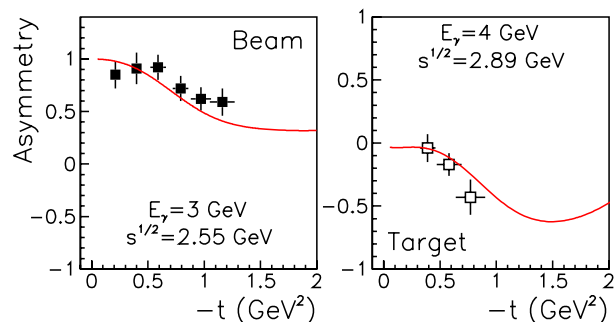
Fig. 3. The beam (filled squares) and target (open squares) asymmetries in photoproduction of η-mesons from protons measured [30,35] at the Daresbury Laboratory. The lines are the results of our model calculation.

squared. Those measurements [30,35] were performed at the Daresbury Laboratory. It is known [30] that polarization data constitute a rather crucial test for models based on Regge phenomenology. Indeed, all model calculations [36,37] available at the time when the experiments were published failed to reproduce the data on the beam asymmetry. The most recent analysis [22] of the $\gamma p \rightarrow p\eta$ reaction is based on a Regge model proposed in 1970 [23] and considers only differential cross-sections at photon energies above 4 GeV, but no polarization data. Furthermore, the ρ-trajectory used in refs. [22,23] is very different from the one determined in our global analysis [38] of the $\pi^- p \rightarrow \pi^0 n$ reaction and from total cross-sections for various other reactions [39]. The lines in fig. 3 are our

results which are clearly in good agreement with the data on beam and target asymmetries.

Obviously, our Regge model reproduces the η photoproduction data on differential cross-sections and polarizations available at photon energies above $\simeq 3$ GeV rather well. We take that as confirmation for the hadronic part of the reaction amplitude to be reliably determined so that it can be used with confidence in the evaluation of the Primakoff effect.

The Primakoff effect [40] is due to the one-photon exchange (OPE) contribution to neutral meson photoproduction. The OPE amplitude F_P is proportional to the two-photon decay width of the η-meson and given by

$$F_P = \frac{8m_p}{t}\sqrt{\frac{\pi\Gamma(\eta\rightarrow\gamma\gamma)}{m_\eta^3}}F_D(t)F_{\eta\gamma\gamma^*}(t), \qquad (3)$$

where m_p and m_η are the proton and η-meson masses, respectively, and Γ is the $\eta\rightarrow\gamma\gamma$ decay width. F_D and $F_{\eta\gamma\gamma^*}$ are form factors at the $pp\gamma^*$ and $\eta\gamma\gamma^*$ vertices, respectively (γ^* signifies the virtual (exchanged) photon). For $F_D(t)$, the Dirac form factor of the proton, we adopt the parameterization given in ref. [41],

$$F_D(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t}\frac{1}{(1-t/t_0)^2} \qquad (4)$$

with $t_0 = 0.71\,\mathrm{GeV}^2$, which is derived under the assumptions that the Dirac form factor F_D of the neutron and the isoscalar Pauli form factor vanish and that a dipole form is satisfactory for $G_M \approx \mu G_E(t)$, cf. [41]. There are slight deviations from the dipole form in the region $-t < 0.5\,\mathrm{GeV}^2$ we are concerned with here, cf. for example ref. [42], but these are negligible for the present study. For the form factor $F_{\eta\gamma\gamma^*}(t)$ we use the parameterization given by the CLEO Collaboration in ref. [43]:

$$|F_{\eta\gamma\gamma^*}(t)|^2 = \frac{1}{(4\pi\alpha)^2}\frac{64\pi\Gamma(\eta\rightarrow\gamma\gamma)}{m_\eta^3}\frac{1}{(1-t/\Lambda^2)^2}. \qquad (5)$$

A fit to their data [43] yielded the value $\Lambda = 0.774\,\mathrm{GeV}$ that is close to the vector dominance model and to the prediction for the soft nonperturbative region given in ref. [44]. For the Primakoff amplitude as given in eq. (3) we have to renormalize this form factor so that $F_{\eta\gamma\gamma^*}(0) = 1$. The amplitude of eq. (3) should be added to the Regge amplitude F_1, cf. refs. [27,28].

Since the OPE contributes essentially only at very small $|t|$ it is sensible to consider the differential cross-section as a function of the center-of-mass (cm) angle and not of the four-momentum transfer squared. This is done in fig. 4 where we include data from DESY at energies of 4 GeV and 6 GeV [23] (open squares) and from Cornell at 4 GeV [26] (inverse triangles). The dashed lines indicate our calculations without the OPE amplitude. It is clear that at angles below $10°$ the data are underestimated, which is a direct indication for the required additional contribution due to the Primakoff amplitude, eq. (3).

Let us now fit the data, taking the $\eta\rightarrow\gamma\gamma$ radiative decay width as free parameter. Unfortunately, there
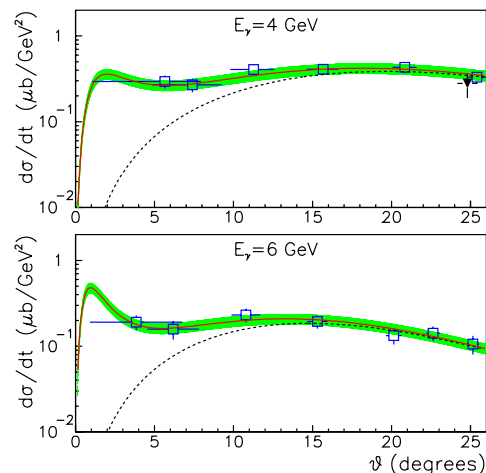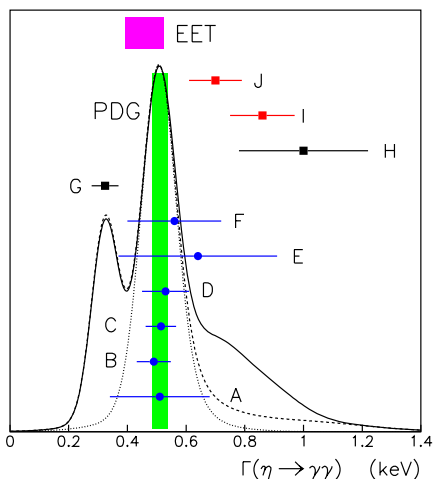

Fig. 4. Differential cross-section for the reaction $\gamma p \rightarrow p\eta$ as a function of the angle ϑ in the cm system for the photon energies $E_\gamma = 4$ and 6 GeV. The data are from DESY [23] (open squares) and Cornell [26] (inverse triangles). The solid (dashed) lines show the results of our Regge calculation with (without) inclusion of the OPE contribution. The shaded band indicates the uncertainty of our results due to the hadronic amplitude.

is no information with regard to the angular resolution of the measurements [23,26]. Only the intervals of the four-momentum squared where the DESY results were obtained are known and those are indicated in fig. 4 as an uncertainty in the cm angle ϑ. Fortunately, below $\vartheta \leq 15°$ the cross-section data exhibit practically no angular dependence so that these uncertainties have no significant influence on our solution. We obtain for the decay width the values $\Gamma(\eta\rightarrow\gamma\gamma) = 0.86 \pm 0.11\,\mathrm{keV}$ at the photon energy of 4 GeV and $\Gamma(\eta\rightarrow\gamma\gamma) = 0.70 \pm 0.09\,\mathrm{keV}$ at $E_\gamma = 6$ GeV. The fit includes all data points shown in fig. 4. A somewhat unpleasant finding is that for both photon energies the fit results in a rather low χ^2, namely χ^2/data point $\simeq 0.3$. For a statistically uncorrelated set of data points one would expect a value around 1. The shaded band in fig. 4 indicates the uncertainty in the employed hadronic amplitude [28].

Keeping in mind possible ambiguities of our results due to the unknown resolution we now compare the $\eta\rightarrow\gamma\gamma$ radiative decay width evaluated here with the world data. Figure 5 contains results from different measurements available in the literature. Specifically, circles indicate data [13–18] determined from the $e^+e^- \rightarrow e^+e^-\eta$ reaction, while the squares are results [19,20] obtained with the Primakoff effect from measurements on nuclear targets. A detailed discussion of the various measurements is given in ref. [21].

Recently, the results from the Cornell measurement [19], indicated by G in fig. 5, were re-analyzed [22] assuming different contributions from incoherent η-meson photoproduction from nuclei which led to an $\eta\rightarrow\gamma\gamma$ radiative decay width of 0.476 keV. This illustrated that the analysis of the data [19] depends significantly on the incoherent background at angles below $\simeq 2^0$ in the laboratory

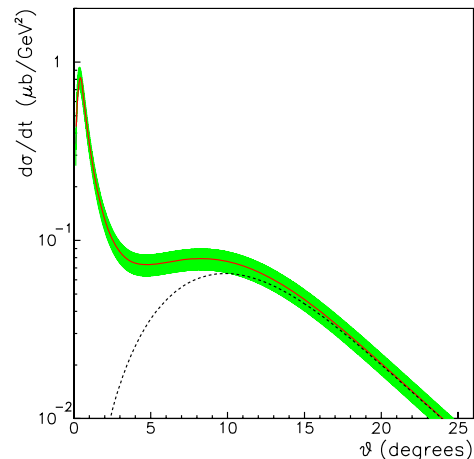**Fig. 5.** The $\eta \to \gamma\gamma$ radiative decay width from different analyses. The results are taken from: A [13], B [14], C [15], D [16], E [17], F [18], G [19], H [20]. Our own results obtained from a fit of the $\gamma p \to \eta p$ differential cross-sections [26,23] at the photon energies of 4 and 6 GeV, are denoted by I and J, respectively. Circles are data obtained from the $e^+e^- \to e^+e^-\eta$ reaction, while squares indicate results obtained by Primakoff-effect measurements. The shaded box, indicated as PDG, is an averaged result [12]. The box indicated as EET shows the limit given by eq. (2). The lines indicate data distribution functions as explained in the text.

Fig. 6. Differential cross-section for the reaction $\gamma p \to p\eta$ as a function of the angle ϑ in the cm system at the photon energy $E_\gamma = 11$ GeV. The solid (dashed) lines show the results of our Regge calculations with (without) inclusion of the one-photon-exchange contribution. The shaded band indicates the uncertainty of our prediction due to the hadronic amplitude.

frame and on the model applied. Clearly, the data obtained [26,23] with a proton target are clean with respect to such background contributions to the Primakoff effect so that our evaluation here should be more reliable. Therefore, we agree with the conclusion of Laget [24] that future measurements with a proton target could be quite promising.

Our results obtained for photon energies of 4 and 6 GeV are indicated in fig. 5 as I and J, respectively[1]. We see that there is a partial conflict between these results and data obtained from the $e^+e^- \to e^+e^-\eta$ measurements. The shaded band in fig. 5 illustrates the averaged result from the PDG [12], based on the measurements A to D. The lines show data distribution functions that were obtained in the following way [12]: to each measurement shown in fig. 5 a Gaussian distribution is assigned with a central value and a dispersion given by the error bar and the integral area proportional to the inverse error bar. The dotted line in fig. 5 represents the sum of the Gaussians for the measurements A to D. The dashed line indicates the sum of the measurements A to H. The solid line is the sum obtained with all data, including our results I and J.

From this data distribution analysis we conclude that even when taking into account all measurements and considering the correction proposed [22] for G, it is still difficult to infer that the $\eta \to \gamma\gamma$ radiative decay width is known now with high accuracy, say 5%, as given by

the PDG [12]. Note that the recent averaged value of $\Gamma(\eta \to \gamma\gamma)$ of the PDG was obtained by neglecting the $e^+e^- \to e^+e^-\eta$ measurements [17,18] indicated as E and F in fig. 5. In addition, the results G and H obtained by the Primakoff measurement were always neglected by the PDG [12] as recommended in ref. [45] without any solid argumentation, solely on the basis that these results are in disagreement with other measurements.

In fig. 6 we display the differential cross-section at forward angles for η-meson photoproduction at the photon energy 11 GeV. This energy was suggested by the PrimEx Collaboration for a future experiment in Hall D at JLab [25]. Here the dashed line is the hadronic contribution alone, while the solid line accounts for the sum of the OPE and the hadronic amplitude. The shaded band indicates the uncertainty of our prediction due to the hadronic amplitude. Note that for this prediction we used the standard value $\Gamma(\eta \to \gamma\gamma) = 0.51$ keV [12]. Obviously, also at higher energies the signal from the Primakoff effect is much larger than the uncertainty in the hadronic amplitude, even up to angles around $\vartheta \approx 5°$, Thus, we believe that it is rather promising to perform further high-precision measurements of the two-photon decay of the η-meson utilizing the Primakoff effect as proposed by the PrimEx Collaboration at JLab [25].

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[1] We remark that the effects of the form factors in eq. (3) is small, setting, e.g., $F_{\eta\gamma\gamma^*}(t)$ to one leads to a few percent shift in the central value for the width, well within the uncertainty induced from the hadronic amplitudes.

References

1. S.L. Adler, Phys. Rev. **177**, 2426 (1969).
2. J.S. Bell, R. Jackiw, Nuovo Cimento A **60**, 47 (1969).
3. W.A. Bardeen, Phys. Rev. **184**, 1848 (1969).
4. J. Wess, B. Zumino, Phys. Lett. B **37**, 95 (1971).
5. E. Witten, Nucl. Phys. B **223**, 422 (1983).
6. J. Bijnens, Int. J. Mod. Phys. A **8**, 3045 (1993).
7. J.L. Goity, A.M. Bernstein, B.R. Holstein, Phys. Rev. D **66**, 076014 (2002).
8. K. Kampf, B. Moussallam, Phys. Rev. D **79**, 076005 (2009).
9. J. Gasser, H. Leutwyler, Nucl. Phys. B **250**, 465 (1985).
10. H. Leutwyler, Nucl. Phys. Proc. Suppl. **64**, 223 (1998).
11. T. Feldmann, Int. J. Mod. Phys. A **15**, 159 (2000).
12. Particle Data Group (C. Amsler *et al.*), Phys. Lett. B **667**, 1 (2008).
13. S.E. Baru *et al.*, Z. Phys. C **48**, 581 (1990).
14. N.A. Roe *et al.*, Phys. Rev. D **41**, 17 (1990).
15. D.A. Williams *et al.*, Phys. Rev. D **38**, 1365 (1988).
16. W. Bartel *et al.*, Phys. Lett. B **160**, 421 (1985).
17. H. Aihara *et al.*, Phys. Rev. D **33**, 844 (1986).
18. A.J. Weinstein *et al.*, Phys. Rev. D **28**, 2896 (1983).
19. A. Browman *et al.*, Phys. Rev. Lett. **32**, 1067 (1974).
20. C. Bemporad *et al.*, Phys. Lett. B **25**, 380 (1967).
21. Particle Data Group (L. Montanet *et al.*), Phys. Rev. D **50**, 1451 (1994).
22. T.E. Rodrigues *et al.*, Phys. Rev. Lett. **101**, 012301 (2008).
23. W. Braunschweig *et al.*, Phys. Lett. B **33**, 236 (1970).
24. J.M. Laget, Phys. Rev. C **72**, 022202(R) (2005).
25. PrimEx Collaboration (A. Gasparian *et al.*), www.jlab.org/primex/primex_notes/PR-09-015.pdf.
26. J. Dewire, B. Gittelman, R. Loe, E.C. Loh, D.J. Ritchie, R.A. Lewis, Phys. Lett. B **37**, 326 (1971).
27. A. Sibirtsev, J. Haidenbauer, S. Krewald, U.-G. Meißner, A.W. Thomas, Eur. Phys. J. A **41**, 71 (2009).
28. A. Sibirtsev, J. Haidenbauer, S. Krewald, U.-G. Meißner, in preparation.
29. V. Crede *et al.*, Phys. Rev. Lett. **94**, 012004 (2005).
30. P.J. Bussey *et al.*, Phys. Lett. B **61**, 479 (1976).
31. R.L. Anderson *et al.*, Phys. Rev. D **1**, 27 (1970).
32. M. Williams *et al.*, Phys. Rev. C **80**, 045213 (2009).
33. I. Jaegle *et al.*, Phys. Rev. Lett. **100**, 252002 (2008).
34. V. Crede *et al.*, Phys. Rev. C **80**, 055202 (2009).
35. P.J. Bussey *et al.*, Nucl. Phys. B **185**, 269 (1981).
36. P.D.B. Collins, A. Fitton, Nucl. Phys. B **68**, 125 (1974).
37. E.N. Argyres *et al.*, Nucl. Phys. B **45**, 267 (1972).
38. F. Huang, A. Sibirtsev, S. Krewald, C. Hanhart, J. Haidenbauer, U-G. Meißner, Eur. Phys. J. A **40**, 77 (2009).
39. J.R. Cudell *et al.*, Phys. Rev. D **65**, 074024 (2002).
40. H. Primakoff, Phys. Rev. **81**, 899 (1951).
41. A. Donnachie, P.V. Landshoff, Nucl. Phys. B **231**, 189 (1984).
42. M.A. Belushkin, H.-W. Hammer, U.-G. Meißner, Phys. Rev. C **75**, 035202 (2007).
43. J. Gronberg *et al.*, Phys. Rev. D **57**, 33 (1998).
44. S.J. Brodsky, G.P. Lepage, Phys. Rev. D **24**, 1808 (1981).
45. B.M.K. Nefkens, J.W. Price, Phys. Scr. T **99**, 114 (2002).