Final state polarization of protons in $pp \to pp\omega$

G. Ramachandran
GVK Academy, Jayanagar, Bangalore 560082, India

Venkataraya[*]
Vijaya College, Bangalore 560011, India

J. Balasubramanyam[*]
K. S. Institute of Technology, Bangalore 560062, India
(Received 29 April 2009; revised manuscript received 27 November 2009; published 1 February 2010)

Model-independent formulas are derived for the polarizations and spin correlations of protons in the final state of $pp \to pp\omega$, taking into consideration all six threshold partial wave amplitudes, $f_1, \ldots, f_6$, covering the Ss, Sp, and Ps channels. It is shown that these measurements of the final state spin observables, employing only an unpolarized beam and an unpolarized target, can be utilized to complement measurements at the double-differential level suggested earlier [J. Balasubramanyam, Venkataraya, and G. Ramachandran, Phys. Rev. C **78**, 012201(R) (2008)] so that all six partial wave amplitudes can be determined empirically.

DOI: 10.1103/PhysRevC.81.027601 PACS number(s): 13.25.−k, 13.60.Le, 13.75.−n, 13.88.+e

Meson production in NN collisions has attracted considerable attention [1] since the early 1990s, when total cross-section measurements [2] for neutral pion production were found to be more than a factor of 5 than the then available theoretical predictions [3]. Experimental studies have indeed reached a high degree of sophistication since then and detailed measurements of the differential cross-section and of spin observables have been carried out employing a polarized beam and a polarized target [4,5]. Apart from the pseudoscalar pion, vector mesons are also known to be significant contributors for the NN interaction. When a meson is produced in the final state, a large momentum transfer is involved, which implies that the NN interaction is probed at very short distances, estimated [6] to be of the order of 0.53, 0.21, and 0.18 fm for the production of π, ω, and φ, respectively. Because the singlet-octet mixing angle is close to the ideal value, the ω-meson wave function is dominated by u and d quarks whereas the strange quark dominates in the case of φ. As a result, the φ-meson production is suppressed as compared to the ω-meson production, according to the Okubo-Zweig-Iizuka (OZI) rule [7]. This rule was, however, found to be violated dramatically in the case of $p\bar{p}$ collisions [8]. Consequently, attention has been focused on the measurement [9–11] of the ratio $R_{\varphi/\omega}$ and its comparison with the theoretical estimates [12]. Apart from Refs. [9–11] measurements of total cross-sections as well as angular distributions for $pp \to pp\omega$ [13] at energies ϵ above threshold up to 320 MeV in c.m., the reaction has also been studied theoretically using several models [14]. A model-independent theoretical approach has also been developed [15] to study the measurements of not only the differential and total cross-sections but also the polarization of ω in the final state. A set of six partial wave amplitudes, $f_1, \ldots, f_6$, has been identified [15] to study $pp \to pp\omega$ at threshold and near threshold energies covering the Ss, Sp, and Ps amplitudes. It has been further shown [16] that the dominant decay mode $\omega \to 3\pi$ can only be utilized to determine the tensor polarization of ω. However, it has also been pointed out [15] that the vector polarizations as well as the tensor polarizations can be measured using the decay $\omega \to \pi^0\gamma$, with the smaller branching ratio of 8.92%. It is encouraging to note that WASA at COSY [17] is expected to facilitate the experimental study of $pp \to pp\omega$ via the detection of $\omega \to \pi^0\gamma$ decay. In view of a recent measurement [18] of the analyzing power A_y for the first time, the model-independent approach was extended [19] to study ω production in pp collisions with a polarized beam. While considering ω production it is worth pointing out that the notation used by Meyer *et al.* [5] in the context of neutral pion production has to be complemented. Because ω is a spin 1 meson, one needs to specify also the total angular momentum $j_\omega = |l-1|, \ldots, l+1$ of the ω meson, where l denotes the orbital angular momentum with which the meson is produced. Moreover, j_ω has to combine with j_f of the two-nucleon system in the final state to yield total angular momentum j of the two-nucleon system in the initial state due to the rotational invariance. This problem has been discussed in Ref. [19] and the amplitudes $f_1, \ldots, f_6$ have explicitly been given in terms of the amplitudes that specify j_f and j_ω. Considering the beam analyzing power A_y and beam to meson spin transfers in addition to the differential cross-section, at the double-differential level, it was shown in Ref. [19] that the lowest three amplitudes, f_1, f_2, and f_3, covering the Ss and Sp channel can be determined empirically without any discrete ambiguity, while information with regard to the amplitudes f_4, f_5, and f_6 covering the Ps channel can only be extracted partially from these measurements.

The purpose of the present article is to demonstrate theoretically that all six amplitudes may be determined empirically without any ambiguities, if some measurements are carried out with regard to the final spin state of the protons in an experiment employing an unpolarized beam and an unpolarized target. We may perhaps mention here

[*]GVK Academy, Jayanagar, Bangalore 560082, India; gwrvrm@yahoo.com

that we do not make any simplifying assumptions as have been made in an older work [20]. It may further be noted that the analysis reported in Ref. [20] made use of the then existing unpolarized differential cross-section measurements at the single-differential level, whereas we are considering here all the observables at the double-differential level as in our more recent work [19]. As such the present article carries forward the analysis reported in Ref. [19] and is not in any way dependent on the much earlier results of Ref. [20].

The reaction matrix $\mathcal{M}$ may be expressed, in a model-independent way [15,19,20], as

$$\mathcal{M} = \sum_{s_f,s_i=0}^{1} \sum_{\lambda=|s_f-s_i|}^{(s_f+s_i)} \sum_{S=1-s_f}^{1+s_f} \sum_{\Lambda=|S-s_i|}^{(S+s_i)} \times ((S^1(1,0) \otimes S^\lambda(s_f,s_i))^\Lambda \cdot \mathcal{M}^\Lambda(Ss_fs_i;\lambda)), \quad (1)$$

where s_i and s_f denote, respectively, the initial and final spin states of the two-nucleon system and S denotes the channel spin in the final state of the reaction. The irreducible tensor amplitudes $\mathcal{M}^\Lambda_\nu(Ss_fs_i;\lambda)$ of rank Λ are explicitly given, in terms of partial wave amplitudes $f_1,\ldots,f_6$, by

$$\mathcal{M}^1_0(101;1) = \frac{1}{24\pi\sqrt{\pi}} f_1, \quad (2)$$

$$\mathcal{M}^1_{\pm 1}(101;1) = 0, \quad (3)$$

$$\mathcal{M}^1_0(100;0) = \frac{1}{8\pi\sqrt{3\pi}} f'_{23}\cos\theta, \quad (4)$$

$$\mathcal{M}^1_{\pm 1}(100;0) = \mp\frac{1}{8\pi\sqrt{6\pi}} f_{23}\sin\theta e^{\pm i\varphi}, \quad (5)$$

$$\mathcal{M}^1_0(110;1) = \frac{1}{8\pi\sqrt{3\pi}} f'_{45}\cos\theta_f, \quad (6)$$

$$\mathcal{M}^1_{\pm}(110;1) = \mp\frac{1}{8\pi\sqrt{6\pi}} f_{45}\sin\theta_f, \quad (7)$$

$$\mathcal{M}^2_0(210;1) = 0, \quad (8)$$

$$\mathcal{M}^2_{\pm 1}(210;1) = -\frac{3}{80\pi\sqrt{3\pi}} f_6\sin\theta_f, \quad (9)$$

$$\mathcal{M}^2_{\pm 2}(210;1) = 0, \quad (10)$$

where the z axis is chosen along the beam, and the plane containing the beam and $\boldsymbol{p}_f = (\boldsymbol{p}_1 - \boldsymbol{p}_2)/2$ is chosen as the z-x plane if $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ denote c.m. momenta of the two protons in the final state. The polar angles of the c.m. momentum of the meson are denoted by (θ,φ). The shorthand notation

$$f_{ij} = f_i + \frac{1}{\sqrt{10}} f_j, \quad (11)$$

$$f'_{ij} = f_i - \frac{2}{\sqrt{10}} f_j, \quad (12)$$

is used with $i, j = 2, 3$ or $4, 5$.

When the beam and the target are unpolarized the spin density matrix ρ^f characterizing the final spin state of the system is given by

$$\rho^f = \tfrac{1}{4}\mathcal{M}\mathcal{M}^\dagger, \quad (13)$$

so that the unpolarized double-differential cross-section is given by

$$\frac{d^2\sigma_o}{dW d\Omega_f d\Omega} = \mathrm{Tr}(\rho^f) \equiv d^2\sigma_0, \quad (14)$$

where the abbreviation $d^2\sigma_0$ is employed for simplicity.

If measurements are not carried out with regard to the spin state of ω, the density matrix

$$\rho = \sum_{\mu=-1}^{1} \langle 1\mu|\rho^f|1\mu\rangle \quad (15)$$

describes the spin state of the protons in the final state. Here $|1\mu\rangle$ denotes the spin state of ω, with magnetic quantum number μ.

It is well known that the state of polarization of two protons is completely specified by measuring the expectation values

$$d^2\sigma_0\, P_\alpha(i) = \mathrm{Tr}[\sigma_\alpha(i)\rho], \quad i = 1, 2, \quad (16)$$

which denote the individual polarizations of the two protons in the final state and their spin correlations

$$d^2\sigma_0\, C_{\alpha,\beta} = \mathrm{Tr}[\sigma_\alpha(1)\sigma_\beta(2)\rho], \quad (17)$$

where α and β denote Cartesian components $\alpha, \beta = x, y, z$. We obtain

$$-P_x(1) = P_x(2) = g\Im(\gamma)\sin\theta\sin\varphi\cos\theta_f, \quad (18)$$

$$P_y(1) = g\left[\frac{\sqrt{3}}{2\sqrt{2}}\Im(\eta_3) - \Im(\gamma)\sin\theta\cos\varphi\cos\theta_f + \Im(\eta_2)\cos\theta\sin\theta_f\right], \quad (19)$$

$$P_y(2) = g\left[\frac{\sqrt{3}}{2\sqrt{2}}\Im(\eta_3) + \Im(\gamma)\sin\theta\cos\varphi\cos\theta_f - \Im(\eta_2)\cos\theta\sin\theta_f\right], \quad (20)$$

$$-P_z(1) = P_z(2) = g\Im(\eta_1)\sin\theta\sin\varphi\sin\theta_f, \quad (21)$$

$$C_{xy} - C_{yx} = 2g\Re(\eta_1)\sin\theta\sin\varphi\sin\theta_f, \quad (22)$$

$$C_{yz} - C_{zy} = -2g\Re(\gamma)\sin\theta\sin\varphi\cos\theta_f, \quad (23)$$

$$C_{zx} - C_{xz} = 2g[\Re(\gamma)\sin\theta\cos\varphi\cos\theta_f - \Re(\eta_2)\cos\theta\sin\theta_f], \quad (24)$$

where

$$\gamma = f_{23} f'^{*}_{45}, \quad (25)$$

$$\eta_1 = f_{23}\left(f_{45} - \frac{3}{\sqrt{50}} f_6\right)^*, \quad (26)$$

$$\eta_2 = f'_{23}\left(f_{45} + \frac{3}{\sqrt{50}} f_6\right)^*, \quad (27)$$

$$\eta_3 = f'_{45}\left(f_{45} - \frac{3}{\sqrt{50}} f_6\right)^*, \quad (28)$$

and

$$g = \frac{\sqrt{6}/32\pi^3}{\mathrm{Tr}(\rho^f)} \quad (29)$$

is known from Eq. (14). Equations (18) to (24) for all the proton spin observables in the final state are derived for the first time. These observables at the double-differential level complement the observables at the double differential considered in Ref. [19].

Experimental measurements of Eqs. (23) and (18) determine, respectively, real and imaginary parts of γ given by Eq. (25). Likewise, Eqs. (22) and (21) determine, respectively, the real and imaginary parts of η_1. Because $\Re(\gamma)$ is known from Eq. (23), the real part of η_2 may be determined from Eq. (24). If we consider $P_y(1) - P_y(2)$, it is clear upon using Eqs. (19) and (20) that $\Im(\eta_2)$ can be determined, because $\Im(\gamma)$ is known from Eq. (18). Taking into consideration these additional inputs together with inputs derived from the measurements discussed earlier in Ref. [19], it is possible to determine all six partial wave amplitudes $f_1, \ldots, f_6$ along with their relative phases empirically.

Let us therefore summarize in Table I the information obtainable from various observables at the double-differential level. We consider the unpolarized differential cross-section, polarization of ω produced, the beam analyzing power, the beam to ω meson spin transfers and the final state spin observables of the pp system, formulas for which have been derived for the first time in this article. The $\alpha, \beta, \zeta, \eta$, and γ are bilinears in f_1, f_{23}, f'_{23}, f_{45}, f'_{45}, and f_6. The explicit forms for η_1, η_2, and η_3 are given by Eqs. (26) to (28), while γ is given by Eq. (25) of the present article. The explicit form for $\alpha_0 = \alpha_4$ is given by Eq. (7) and Eq. (19) of Ref. [19]. We may rewrite $\alpha_2, \alpha_3, \alpha_5$, and α_6 given by Eqs. (7), (19), (20), and (21) of Ref. [19] as

$$\alpha_2 = |f_3|^2 - 2\sqrt{10}\Re(f_2 f_3^*) = \frac{10}{3}(|f'_{23}|^2 - |f_{23}|^2), \tag{30}$$

$$\alpha_3 = \Im(f_2 f_3^*) = -\frac{\sqrt{10}}{3}\Im(f_{23} f_{23}^*), \tag{31}$$

$$\alpha_5 = |f_2|^2 + \frac{3}{10}|f_3|^2 - \frac{2}{\sqrt{10}}\Re(f_2 f_3^*) = \frac{1}{3}(|f_{23}|^2 + 2|f'_{23}|^2), \tag{32}$$

$$\alpha_6 = |f_2|^2 - \frac{1}{5}|f_3|^2 - \frac{1}{\sqrt{10}}\Re(f_2 f_3^*) = \Re(f_{23} f_{23}^*). \tag{33}$$

The explicit forms for $\beta_1, \ldots, \beta_5$ are given in Eqs. (12), (37), and (38) of Ref. [19], while those for $\zeta_0, \zeta_2, \ldots, \zeta_7$ are given by Eqs. (8), (22), ..., (26) of Ref. [19].

We readily find that

$$|f_1|^2 = \beta_3. \tag{34}$$

We can choose the phase of f_1 to be zero without any loss of generality so that f_1 is known empirically from Eq. (34). We denote the relative phases of f_{23}, f'_{23}, f_{45}, f'_{45}, and f_6 with respect to f_1 as $\varphi_{23}, \varphi'_{23}, \varphi_{45}, \varphi'_{45}$, and φ_6, respectively. We readily see that

$$|f_{23}|^2 = \alpha_7, \tag{35}$$

whereas φ_{23} is given, without any trigonometric ambiguity, by

$$\cos\varphi_{23} = \frac{\beta_2}{f_1|f_{23}|}, \quad \sin\varphi_{23} = \frac{\beta_1}{f_1|f_{23}|}. \tag{36}$$

Thus f_{23} is known empirically. Likewise we find that

$$|f'_{23}|^2 = \alpha_7 + 0.3\alpha_2, \tag{37}$$

$$\cos\varphi'_{23} = \frac{\beta_4}{f_1|f'_{23}|}, \quad \sin\varphi'_{23} = -\frac{\beta_5}{f_1|f'_{23}|}, \tag{38}$$

which determine f'_{23} empirically. Similarly

$$|f_{45}|^2 = \left|\frac{f_{23}\eta_2 + f'_{23}\eta_1}{2 f_{23} f'_{23}}\right|^2, \tag{39}$$

$$\cos\varphi_{45} = \frac{1}{2f_1|f_{45}|}\left(\frac{\beta_2\Re\eta_1 + \beta_1\Im\eta_1}{|f_{23}|^2} + \frac{\beta_4\Re\eta_2 - \beta_5\Im\eta_2}{|f'_{23}|^2}\right), \tag{40}$$

$$\sin\varphi_{45} = \frac{1}{2f_1|f_{45}|}\left(\frac{\beta_1\Re\eta_1 - \beta_2\Im\eta_1}{|f_{23}|^2} - \frac{\beta_5\Re\eta_2 + \beta_4\Im\eta_2}{|f'_{23}|^2}\right), \tag{41}$$

which determine f_{45} empirically. We next note that

$$|f'_{45}|^2 = \zeta_0 + \zeta_2 = \zeta_5 - \zeta_4, \tag{42}$$

where

$$\zeta_0 = \tfrac{1}{2}\zeta_7 + \tfrac{1}{27}(a-b), \zeta_4 = -\tfrac{1}{2}\zeta_7 + \tfrac{2}{27}(a-b), \tag{43}$$

in terms of the entities listed in the second column of Table I. Moreover,

$$\cos\varphi'_{45} = \frac{\beta_2\Re\gamma + \beta_1\Im\gamma}{f_1|f'_{45}||f_{23}|^2}, \sin\varphi'_{45} = \frac{\beta_1\Re\gamma - \beta_2\Im\gamma}{f_1|f'_{45}||f_{23}|^2}, \tag{44}$$

TABLE I. Observables in $pp \to pp\omega$ at double-differential level.

Serial no.	Observables and their theoretical formulas	Entities determinable from experimental measurements
1	Unpolarized double differential cross-section: $d^2\sigma_0 = \frac{1}{768\pi^3}(a + 0.9\alpha_2\cos^2\theta + 9\zeta_2\cos^2\theta_f)$	$a = (\alpha_0 + 9\zeta_0)$ α_2, ζ_2
2	Vector polarization of ω: $C_0(t^1_{\pm1})_0 = \frac{9i}{4}(\frac{2}{\sqrt{10}}\alpha_3\sin 2\theta + \zeta_3\sin 2\theta_f e^{\pm i\varphi_f})$	α_3, ζ_3
3	Tensor polarization of ω: $C_0(t^2_0)_0 = \frac{1}{\sqrt{6}}(b - 9\alpha_5\cos^2\theta + \zeta_5\cos^2\theta_f)$ $C_0(t^2_{\pm1})_0 = \pm\frac{3}{4}(2\alpha_6\sin 2\theta - 3\zeta_6\sin 2\theta_f e^{\pm i\varphi_f})$ $C_0(t^2_{\pm2})_0 = -\frac{3}{4}(2\alpha_7\sin^2\theta - 3\zeta_7\sin^2\theta_f e^{\pm 2i\varphi_f})$	$b = (\alpha_4 - 9\zeta_4)$ α_5, ζ_5 α_6, ζ_6 α_7, ζ_7
4	Beam analyzing power: $C_0\vec{A} = \sqrt{2}\beta_1(\hat{q}\times\hat{p}_i)$	β_1
5	Beam to ω spin transfers: $C_0K^x_x = C_0K^y_y = -\beta_4\cos\theta$, $C_0K^z_x = \sqrt{2}\beta_2\sin\theta$ $C_0K^z_z = \frac{1}{\sqrt{3}}\beta_3$ $C_0K^{xx}_y = -2C_0K^{yy}_y = -2C_0K^{zz}_y = -2\sqrt{2}\beta_1\sin\theta$ $C_0K^{xz}_y = -C_0k^{yz}_x = -\frac{3}{\sqrt{2}}\beta_5\cos\theta$	β_4 β_2 β_3 β_1 β_5
6	Final state polarization of two protons: Eqs. (18) to (23) of the present article	η_1, η_2, η_3, and γ

which together with Eq. (42) determine f'_{45} empirically. Finally

$$|f_6|^2 = \frac{25}{18}\left|\frac{f_{23}\eta_2 - f'_{23}\eta_1}{f_{23}f'_{23}}\right|^2, \tag{45}$$

$$\cos\varphi_6 = \frac{5\sqrt{2}}{6f_1|f_6|}\left[\frac{\beta_4\Re\eta_2 - \beta_5\Im\eta_2}{|f'_{23}|^2} - \frac{\beta_2\Re\eta_1 + \beta_1\Im\eta_1}{|f_{23}|^2}\right], \tag{46}$$

$$\sin\varphi_6 = -\frac{5\sqrt{2}}{6f_1|f_6|}\left[\frac{\beta_5\Re\eta_2 + \beta_4\Im\eta_2}{|f'_{23}|^2} + \frac{\beta_1\Re\eta_1 - \beta_2\Im\eta_1}{|f_{23}|^2}\right], \tag{47}$$

which determine f_6 empirically. Thus we see from Eqs. (34), (35), (37), (39), (42), and (45) that the moduli of $f_1, f_{23}, f'_{23}, f_{45}, f'_{45}$, and f_6 can be determined. The relative phases of $f_{23}, f'_{23}, f_{45}, f'_{45}$, and f_6 are determinable with respect to f_1 using Eqs. (36), (38), (40), (41), (44), (46), and (47) without any trigonometric ambiguity, choosing f_1 to be real without any loss of generality. Therefore the amplitudes $f_1, f_{23}, f'_{23}, f_{45}, f'_{45}$, and f_6 are determinable purely empirically.

It may be noted that $|f_1|$ is determined directly from a measurement of the beam to meson spin transfer K^z_z. The $|f_{23}|$ and $|f'_{23}|$ are determinable from the measurements of the unpolarized differential cross-section and the tensor polarization of ω The determination of relative phases of f_{23} and f'_{23} with respect to f_1 involve measurement of beam to meson spin transfers. The $|f'_{45}|$ is determinable from unpolarized differential cross-section and tensor polarization of ω. The determination of relative phases φ'_{45} as well as φ_6 involve proton spin measurements in the final state that are advocated for the first time in the present article.

Having determined f_{ij} and $f'_{ij}, i, j = 2, 3$ or $4, 5$ we may readily obtain f_i and f_j individually through

$$\begin{pmatrix} f_i \\ f_j \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 2 & 1 \\ \sqrt{10} & -\sqrt{10} \end{pmatrix}\begin{pmatrix} f_{ij} \\ f'_{ij} \end{pmatrix}. \tag{48}$$

Thus, one can determine all six partial wave amplitudes, $f_1, \ldots, f_6$, purely empirically in terms of entities (listed in column 2 of Table I) that are extracted from the experimental measurements (listed in column 1 of Table I) at the double-differential level.

We thank the referees for comments on the manuscript. One of us (JB) thanks Principal T. G. S. Moorthy and the management of K. S. Institute of Technology for encouragement and another (Venkataraya) acknowledges much encouragement for research given by the principal and the management of Vijaya College.

[1] H. Machner and J. Haidenbauer, J. Phys. G: Nucl. Part. Phys. **25**, R231 (1999); P. Moskal, M. Wolke, A. Khoukaz, and W. Oelert, Prog. Part. Nucl. Phys. **49**, 1 (2002); G. Faldt, T. Johnson, and C. Wilkin, Phys. Scr. **T99**, 146 (2002); C. Hanhart, Phys. Rep. **397**, 155 (2004).
[2] H. O. Meyer *et al.*, Phys. Rev. Lett. **65**, 2846 (1990); Nucl. Phys. **A539**, 633 (1992).
[3] D. Koltun and A. Reitan, Phys. Rev. **141**, 1413 (1966); M. E. Schillaci, R. R. Silbar, and J. E. Young, Phys. Rev. Lett. **21**, 711 (1968); Phys. Rev. **179**, 1539 (1969).
[4] B. V. Przewoski *et al.*, Phys. Rev. C **61**, 064604 (2000); W. W. Daehnick *et al.*, *ibid.* **65**, 024003 (2002).
[5] H. O. Meyer *et al.*, Phys. Rev. C **63**, 064002 (2001).
[6] K. Nakayama, Matter Mater. **11**, 119 (2002); K. Tsushima and K. Nakayama, Phys. Rev. C **68**, 034612 (2003).
[7] S. Okubo, Phys. Lett. **B5**, 165 (1963); G. Zweig, CERN Report 8419/TH412, 1964; I. Izuka, Prog. Theor. Phys. Suppl. **37**, 21 (1966).
[8] C. Amsler, Rev. Mod. Phys. **70**, 1293 (1998).
[9] F. Balestra *et al.*, Phys. Rev. Lett. **81**, 4572 (1998).
[10] F. Balestra *et al.*, Phys. Rev. C **63**, 024004 (2001).
[11] M. Hartmann *et al.*, Phys. Rev. Lett. **96**, 242301 (2006).
[12] H. J. Lipkin, Phys. Lett. **B60**, 371 (1976); J. Ellis, M. Karliner, D. E. Kharzeev, and M. G. Sapozhnikov, *ibid.* **B353**, 319 (1995); C. Fuchs *et al.*, Phys. Rev. C **67**, 025202 (2003); K. Tsushima and K. Nakayama, *ibid.* **68**, 034612 (2003); L. P. Kaptari and B. Kampfer, Eur. Phys. J. A **23**, 291 (2005).
[13] F. Hibou *et al.*, Phys. Rev. Lett. **83**, 492 (1999); S. Abd E-Samad *et al.* (COSY-TOF Collaboration), Phys. Lett. **B522**, 16 (2001); K. Th. Brinkmann *et al.*, Acta Phys. Pol. B **29**, 2993 (1998); M. Schulte-Wissermann, doctoral dissertation, Technschen Universitat, Dresden, 2004 (unpublished); S. Barsov *et al.*, Eur. Phys. J. A **31**, 95 (2007).
[14] R. Koniuk, Nucl. Phys. **B195**, 452 (1982); P. Stassart and F. Stancu, Phys. Rev. D **42**, 1521 (1990); S. Capstick and W. Roberts, *ibid.* **49**, 4570 (1994); G. Faldt and C. Wilkin, Phys. Lett. **B382**, 209 (1996); A. A. Sibirtsev, Nucl. Phys. **A604**, 455 (1996); N. Kaiser, Phys. Rev. C **60**, 057001 (1999); K. Nakayama, J. W. Durso, J. Haidenbauer, C. Hanhart, and J. Speth, *ibid.* **60**, 055209 (1999); A. A. Sibirtsev and E. Cassing, Eur. Phys. J. A **7**, 407 (2000); A. I. Titov, B. Kampfer, and B. I. Reznik, *ibid.* **7**, 543 (2000); K. Nakayama, J. Haidenbauer, and J. Speth, Phys. Rev. C **63**, 015201 (2000); C. Fuchs *et al.*, *ibid.* **67**, 025202 (2003); K. Tsushima and K. Nakayama, Nucl. Phys. **A721**, 633 (2003); L. P. Kaptaria and B. Kampfer, Eur. Phys. J. A **23**, 291 (2005); A. A. Sibirtsev, J. Haidenbauer, and Meibner, *ibid.* **27**, 263 (2006).
[15] G. Ramachandran, M. S. Vidya, P. N. Deepak, J. Balasubramanyam, and Venkataraya, Phys. Rev. C **72**, 031001(R) (2005).
[16] G. Ramachandran, J. Balasubramanyam, S. P. Shilpashree, and G. Padmanabha, J. Phys. G: Nucl. Part. Phys. **34**, 661 (2007).
[17] H. H. Adam *et al.* (WASA at COSY Collaboration), arXiv:nucl-ex/0411038 (2004).
[18] M. Abdel-Bary *et al.* (COSY-TOF Collaboration), Phys. Lett. **B662**, 14 (2008).
[19] J. Balasubramanyam, Venkataraya, and G. Ramachandran, Phys. Rev. C **78**, 012201(R) (2008).
[20] G. Ramachandran, J. Balasubramanyam, M. S. Vidya, and Venkataraya, Mod. Phys. Lett. A **21**, 2009 (2006).