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

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

Venkataray
Vijaya College, Bangalore-560011, India

J. Balasubramayan
K.S. Institute of Technology, Bangalore, 560062, India

(Dated: November 27, 2009)

Model independent formulae are derived for the polarizations and spin correlations of protons in the final state of $pp \rightarrow pp\omega$, taking into consideration all the six threshold partial wave amplitudes $f_1, \ldots, f_6$ covering $Ss, Sp$ and $Ps$ channels. It is shown that these measurements of the final state spin observables, employing only an unpolarized beam and an unpolarized target, may be utilized to complement measurements, at the double differential level, suggested earlier [Phys. Rev. C78, 01210(R)(2009)] so that all the six partial wave amplitudes may be determined empirically.

PACS numbers: 13.25.-k, 13.60.Le, 13.75.-n, 13.88.+e, 24.70.+s, 25.40.ve

Meson production in $NN$ collisions has attracted considerable attention \[1\] since the early 1990’s, 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 fm, 0.21 fm and 0.18 fm for the production of $\pi, \omega$, and $\varphi$ respectively. Since, the singlet-octet mixing angle is close to the ideal value, the $\omega$ meson wave function is dominated by $u$ and $d$ quarks while the strange quark dominates in the case of $\varphi$. As a result, the $\varphi$ meson production is suppressed as compared to the $\omega$ meson production, according to the Okubo-Zweig-Iizuka (OZI) rule \[7\]. This rule was, however, found to be violated dramatically in the case of $pp$ collisions \[8\]. Consequently, attention has been focused on the measurement \[9, 10, 11\] of the ratio $R_{\varphi/\omega}$ and its comparison with the theoretical estimates \[12\]. Apart from \[9, 10, 11\] measurements of total cross-section as well as angular distributions for $pp \rightarrow pp\omega$ \[13\] at energies $\epsilon$ 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 $\omega$ in the final state. A set of six partial wave amplitudes $f_1, \ldots, f_6$ have been identified \[16\] to study $pp \rightarrow pp\omega$ at threshold and near threshold energies covering the $Ss, Sp$ and $Ps$ amplitudes. It was further shown \[17\] that the dominant decay mode $\omega \rightarrow 3\pi$ can only be utilized to determine the tensor polarization of $\omega$.

It is encouraging to note that WASA \[17\] at COSY is expected to facilitate the experimental study of $pp \rightarrow pp\omega$ via the detection of $\omega \rightarrow \pi^0\gamma$ 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 $\omega$ production in $pp$-collisions with a polarized beam. While considering $\omega$ production it is worth pointing out that the notation used by Meyer et al., \[3\] in the context of neutral pion production has to be complemented. Since $\omega$ is a spin 1 meson, one needs to specify also the total angular momentum $j_\omega = |l - 1|, \ldots, l + 1$ of the $\omega$ meson where $l$ denote the orbital angular momentum with which the meson is produced. Moreover $j_\omega$ has to combine with $jj$ 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 \[19\] and the amplitudes $f_1, \ldots, f_6$ have explicitly been given in terms of the amplitudes which specify $jj$ and $j_\omega$. 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 \[19\] that the lowest three amplitudes $f_1, f_2, f_3$ covering the $Ss$ and $Sp$ channel can be determined empirically without any discrete ambiguity, while information with regard to the amplitudes $f_4, f_5, f_6$ covering the $Ps$ channel can only be extracted partially from these measurements.

*GVK Academy, Jayanagar, Bangalore-560082, India
The purpose of the present paper is to demonstrate theoretically that all the 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 that we do not make any simplifying assumptions as has been made in an older work \cite{20}. It may further be noted that the analysis reported in \cite{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 \cite{19}. As such the present paper carries forward the analysis reported in \cite{19} and is not in any way dependent on the much earlier results of \cite{20}.

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

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

(1)

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

$$
M^0_{10}(101; 1) = \frac{1}{24\pi \sqrt{\pi}} f_1, \\
M^0_{21}(101; 1) = 0, \\
M^0_{10}(100; 0) = \frac{1}{8\pi \sqrt{3\pi}} f'_{23} \cos \theta, \\
M^0_{10}(100; 0) = \mp \frac{1}{8\pi \sqrt{6\pi}} f_{23} \sin \theta e^{\pm i \varphi}, \\
M^0_{01}(110; 1) = \frac{1}{8\pi \sqrt{3\pi}} f'_{45} \cos \theta_f, \\
M^1_{10}(110; 1) = \frac{1}{8\pi \sqrt{6\pi}} f_{45} \sin \theta_f, \\
M^1_{02}(210; 1) = 0, \\
M^1_{21}(210; 1) = -\frac{3}{80\pi \sqrt{3\pi}} f_6 \sin \theta_f, \\
M^2_{22}(210; 1) = 0,
$$

(2-10)

where the $z$-axis is chosen along the beam, and the plane containing the beam and $p_f = (p_1 - p_2)/2$ is chosen as the $z$-$x$ plane if $p_1$ and $p_2$ 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 $(\theta, \varphi)$. The shorthand notation

$$
f_{ij} = f_i + \frac{1}{\sqrt{10}} f_j, \\
\ f'_{ij} = f_i - \frac{2}{\sqrt{10}} f_j,
$$

(11-12)

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

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

$$
\rho^f = \frac{1}{4} M M^\dagger,
$$

(13)

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

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

(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 $\omega$, the density matrix
\[
\rho = \sum_{\mu=-1}^{1} (1\mu|\rho^f|1\mu),
\]
describes the spin state of the protons in the final state. Here $|1\mu\rangle$ denotes the spin state of $\omega$, with magnetic quantum number $\mu$.

It is well known that the state of polarization of two protons is completely specified by measuring the expectation values
\[
d^2\sigma_0 P_{\alpha}(i) = Tr[\sigma_{\alpha}(i)\rho], \quad i = 1, 2,
\]
which denote the individual polarizations of the two protons in the final state and their spin correlations
\[
d^2\sigma_0 C_{\alpha,\beta} = Tr[\sigma_{\alpha}(1)\sigma_{\beta}(2)\rho],
\]
where $\alpha, \beta$ denote Cartesian components $\alpha, \beta = x, y, z$. We obtain
\[
- P_x(1) = P_x(2) = g \Im(\gamma) \\
\times \sin \theta \sin \varphi \cos \theta f,
\]
\[
P_y(1) = g \left[ \frac{\sqrt{3}}{2\sqrt{2}} \Im(\eta_3) \right. \\
- \Im(\gamma) \sin \theta \cos \varphi \cos \theta f \\
+ \Im(\eta_2) \cos \theta \sin \theta f],
\]
\[
P_y(2) = g \left[ \frac{\sqrt{3}}{2\sqrt{2}} \Im(\eta_3) \right. \\
+ \Im(\gamma) \sin \theta \cos \varphi \cos \theta f \\
- \Im(\eta_2) \cos \theta \sin \theta f],
\]
\[
- P_z(1) = P_z(2) = g \Re(\eta_1) \\
\times \sin \theta \sin \varphi \sin \theta f,
\]
\[
C_{xy} - C_{yx} = 2g \Re(\eta_1) \\
\times \sin \theta \sin \varphi \sin \theta f,
\]
\[
C_{yz} - C_{zy} = -2g \Re(\gamma) \\
\times \sin \theta \sin \varphi \cos \theta f,
\]
\[
C_{zx} - C_{xz} = 2g \\
\times [\Re(\gamma) \sin \theta \cos \varphi \cos \theta f \\
- \Re(\eta_2) \cos \theta \sin \theta f],
\]
where
\[
\gamma = f_{23} f_{45}^*,
\]
\[
\eta_1 = f_{23} (f_{45} - \frac{3}{\sqrt{50}} f_{6})^*,
\]
\[
\eta_2 = f_{23}' (f_{45} + \frac{3}{\sqrt{50}} f_{6})^*,
\]
\[
\eta_3 = f_{45}' (f_{45} - \frac{3}{\sqrt{50}} f_{6})^*.
\]
and
\[
g = \frac{\sqrt{\eta}/32\pi^3}{Tr(\rho^f)}
\]
is known from Eq. (14). The above formulae (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 (19).

Experimental measurements of (23) and (18) determine respectively real and imaginary parts of \( \gamma \) given by (25). Likewise, (22) and (21) determine respectively the real and imaginary parts of \( \eta \). Since \( \Re(\gamma) \) is known from (23), the real part of \( \eta \) may be determined from (22). If we consider \( P_y(1) - P_y(2) \), it is clear on using (19) and (20) that \( \Im(\eta) \) can be determined, since \( \Im(\gamma) \) is known from (18). Taking into consideration these additional inputs together with inputs derived from the measurements discussed earlier in (14), it is possible to determine all the 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 \( \omega \) produced, the beam analysing power, the beam to \( \omega \) meson spin transfers and the final state spin observables of the \( pp \) system, formulae for which have been derived for the first time in this paper. The \( \alpha, \beta, \zeta, \eta \) and \( \gamma \) are bilinears in \( f_1, f_{23}, f_{23}', f_{45}, f_{45}' \) and \( f_6 \). The explicit forms for \( \eta_1, \eta_2, \eta_3 \) are given by Eqs. (20) to (23), while \( \gamma \) is given by Eq. (25) of the present paper. The explicit form for \( \alpha_0 = \alpha_4 \) is given by Eq. (7) and Eq. (19) of (14). We may re-write \( \alpha_2, \alpha_3, \alpha_5 \) and \( \alpha_6 \) given by Eqs. (7),

| Sl. | Observables and their Entities determinable from experimental measurements |
|-----|--------------------------------------------------------------------------|
| 1   | Unpolarized double differential cross-section: \( d^2\sigma_0 = \frac{1}{\pi s\sin^2 \theta_f} [a + 0.9\alpha_2 \cos^2 \theta + 9\zeta_2 \cos^2 \theta_f] \) |
|     | \( a = (\alpha_0 + 9\zeta_0), \alpha_2, \zeta_2 \) |
| 2   | Vector polarization of \( \omega \): \( C_0(t_{11})_0 = \frac{a}{4} [2\alpha_3 \sin 2\theta + \zeta_3 \sin 2\theta_f e^{\pm i\phi_f}] \) |
|     | \( \alpha_3, \zeta_3 \) |
| 3   | Tensor polarization of \( \omega \): \( C_0(t_{11})_0 = \frac{b}{4} [2\alpha_5 \sin 2\theta - 3\zeta_5 \sin 2\theta_f e^{\pm i\phi_f}] \) |
|     | \( \alpha_5, \zeta_5 \) |
|     | \( C_0(t_{22})_0 = \frac{c}{4} [2\alpha_7 \sin^2 \theta - 3\zeta_7 \sin^2 \theta_f e^{\pm i\phi_f}] \) |
|     | \( \alpha_7, \zeta_7 \) |
| 4   | Beam analyzing power: \( C_0 = \sqrt{2}\beta_1 (\hat{q} \times \hat{p}_i) \) |
|     | \( \beta_1 \) |
| 5   | Beam to \( \omega \) spin transfers: \( C_0 K^x_x = \beta_4, C_0 K^y_y = \beta_4 \) |
|     | \( C_0 K^z_z = \sqrt{2}\beta_2 \sin \theta, C_0 K^z_z = \beta_3 \) |
|     | \( C_0 K^{xy}_{xy} = -2C_0 K_{yy} = -2C_0 K^{xz}_{xz} = -2\sqrt{2}\beta_1 \sin \theta \) |
|     | \( C_0 K^{xy}_{xy} = -C_0 K_{xz} = -\frac{3}{4}\beta_3 \cos \theta \) |
| 6   | Final state polarization of two protons Eqs. (18) to (23) \( \eta_1, \eta_2, \eta_3 \) and \( \gamma \) of the present paper |
\( \alpha_2 = |f_3|^2 - 2\sqrt{10} \Re(f_2 f_3^*) = \frac{10}{3}(|f_2'|^2 - |f_{23}|^2) \) (30)

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

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

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

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

We readily find that
\( |f_1|^2 = \beta_3 \) (34)

We may 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 \( \varphi_6 \) respectively. We readily see that
\( |f_{23}|^2 = \alpha_7 \) (35)

whereas \( \varphi_{23} \) is given, without any trigonometric ambiguity, by
\[
\cos\varphi_{23} = \frac{\beta_2}{f_1|f_{23}|}; \quad \sin\varphi_{23} = -\frac{\beta_1}{f_1|f_{23}|}
\] (36)

Thus \( f_{23} \) is known empirically. Likewise we find that
\( |f_{23}'|^2 = \alpha_7 + 0.3\alpha_2 \) (37)

\[
\cos\varphi_{23}' = \frac{\beta_4}{f_1|f_{23}'|}; \quad \sin\varphi_{23}' = -\frac{\beta_5}{f_1|f_{23}'|}
\] (38)

which determine \( f_{23}' \) empirically. Similarly
\[
|f_{45}|^2 = \left| \frac{f_{23} \eta_2 + f_{23}' \eta_1}{2 f_{23} f_{23}'} \right|^2
\] (39)

\[
\cos\varphi_{45} = \frac{1}{2 f_1|f_{45}|}
\times \left[ \frac{\beta_2 \Re\eta_1 + \beta_1 \Im\eta_1}{|f_{23}|^2} + \frac{\beta_3 \Re\eta_2 - \beta_5 \Im\eta_2}{|f_{23}'|^2} \right],
\] (40)

\[
\sin\varphi_{45} = \frac{1}{2 f_1|f_{45}|}
\times \left[ \frac{\beta_1 \Re\eta_1 - \beta_2 \Im\eta_1}{|f_{23}|^2} + \frac{\beta_5 \Re\eta_2 + \beta_4 \Im\eta_2}{|f_{23}'|^2} \right]
\] (41)

determine \( f_{45} \) empirically. We next note that
\( |f_{45}'|^2 = \zeta_0 + \zeta_2 = \zeta_5 - \zeta_4 \) (42)

where
\[
\zeta_0 = \frac{1}{2} \zeta_7 + \frac{1}{27} (a - b) \quad ; \quad \zeta_4 = -\frac{1}{2} \zeta_7 + \frac{2}{27} (a - b)
\] (43)
in terms of the entities listed in the second column of Table I. Moreover,

$$\cos \phi_{45} = \frac{\beta_2 \Re \gamma + \beta_1 \Im \gamma}{f_1|f_{45}|f_{23}|^2}; \quad \sin \phi_{45} = \frac{\beta_1 \Re \gamma - \beta_2 \Im \gamma}{f_1|f_{45}|f_{23}|^2}$$

(44)

which together with (42) determine $f_i$ empirically. Finally

$$|f_6|^2 = \frac{25}{18} \left| \frac{f_{23} \eta_2 - f_{23} \eta_1}{f_{23} f_{23}^*} \right|^2,$$

$$\cos \phi_6 = \frac{5 \sqrt{2}}{6 f_1 |f_6|} \times \left[ \frac{\beta_1 \Re \eta_2 - \beta_5 \Im \eta_2}{|f_{23}|^2} - \frac{\beta_2 \Re \eta_1 + \beta_1 \Im \eta_1}{|f_{23}|^2} \right],$$

$$\sin \phi_6 = -\frac{5 \sqrt{2}}{6 f_1 |f_6|} \times \left[ \frac{\beta_3 \Re \eta_2 + \beta_4 \Im \eta_2}{|f_{23}|^2} + \frac{\beta_1 \Re \eta_1 - \beta_2 \Im \eta_1}{|f_{23}|^2} \right],$$

(45) (46) (47)

which determine $f_6$ empirically. Thus we see from Eqs. (44), (45), (46), (47) and (48) 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. (20), (25), (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 $K_2^+$. The $|f_{23}|$ and $|f_{23}^*|$ are determinable from the measurements of the unpolarized differential cross-section and the tensor polarization of $\omega$. 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 $\omega$. The determination of relative phases $\phi_{45}$ as well as $\phi_6$ involve proton spin measurements in the final state which are advocated for the first time in the present paper.

Having determined $f_{ij}$ and $f_{ij}^*, i, j = 2, 3$ or 4, 5 we may readily obtain $f_1$ and $f_j$ individually through

$$\begin{pmatrix} f_1 \\ f_j \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2 & 1 \\ \sqrt{10} & -\sqrt{10} \end{pmatrix} \begin{pmatrix} f_{ij} \\ f_{ij}^* \end{pmatrix}$$

(48)

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

**Acknowledgments**

One of us, (JB) thanks Principal T. G. S. Moorthy and the Management of K. S. Institute of technology for encouragement and another (Venkataraaya) acknowledges much encouragement for research given by the Principal and the Management of Vijnaya College.

[1] H. Machner and J. Haidenbauer, J. Phys. G: Nucl. Part Phys. 25, R231 (1999); P. Moskal, M. Wolke, A. Khouchaz 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); H. O. Meyer et al., Nucl. Phys. A539, 633 (1992).

[3] D. Koltun and A. Reitan, Phys. Rev. 141, 1413 (1966); M. E. Schillaci, R. R. Silbar J. E. Young, Phys. Rev. Lett. 21, 711 (1968); Phys. Rev. 179, 1539 (1969).

[4] B. V. Prezewoski et al., Phys. Rev. C61, 064604(2000); W. W. Daehnick et al., Phys. Rev. C65, 024603 (2002).

[5] H. O. Meyer et al., Phys. Rev. C63, 064002 (2001).

[6] K. Nakayama, Proceedings of the Symposium on Threshold Meson Production in pp and pd Interactions, Schriften des Forschungszentrum Julich [Matter and 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. C63, 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, Phys. Lett. B353, 319 (1995); C. Fuchs et al., Phys. Rev. C67, 025202 (2003); K. Tsushima and K. Nakayama, Phys. Rev. C68, 034612 (2003); L. P. Kaptari and B. Kampfer, Eur. Phys. J. A23, (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. B29, 2993 (1998); Martin Schulte-Wissermann, Doctoral dissertation (unpublished), Technischen Universitat, Dresden (2004); S. Barsov et al., Eur. Phys. J. A31, 95 (2007).
[14] R. Koniuk, Nucl. Phys. B195, 452 (1982); P. Strauss and F. Stancu, Phys. Rev. D42, 1521 (1990); S. Capstick and W. Roberts, ibid. 49, 4570 (1994); G. Falt and C. Wilkin, Phys. Lett. B382, 209 (1996); A. A. Sibirtsev, Nucl. Phys. A604, 455 (1996); N. Kaiser, Phys. Rev. C60, 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. C63, 015201 (2000); C. Fuchs et al., ibid 66, 025202 (2002); 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 and J. Haidenbauer and Meibner, ibid. 27, 263 (2006).
[15] G. Ramachandran, M. S. Vidya, P. N. Deepak, J. Balasubramanyam and Venkataraya, Phys. Rev. C72, 031001 (R) (2005).
[16] G. Ramachandran, J. Balasubramanyam, S. P. Shilpashree and G. Padmanabha, J. Phys. G: Nucl. Part. Phys. 34, 661 (2007).
[17] WASA at COSY Proposal, Eds. B. Höistad and J. Ritman, [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. C78, 012201(R) (2008).
[20] G. Ramachandran, J. Balasubramanyam, M. S. Vidya and Venkataraya Mod. Phys. Lett. A21, 2009 (2006).