On the sign of the $\pi\rho\omega$ coupling constant

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It is shown that the relative sign between the $NN\omega$ and $\pi\rho\omega$ coupling constants can be determined most sensitively from $\omega$ production processes in $NN$ collisions. Recent data on these reactions clearly favor the sign of the $\pi\rho\omega$ coupling constant which is opposite to that inferred from studies of the photoproduction reaction in combination with the vector meson dominance assumption and used by many authors. Implication of this finding in the description of other reactions is discussed.

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A reliable description of hadronic reactions involving the production of $\pi$, $\rho$ or $\omega$ mesons based on meson and baryon degrees-of-freedom usually requires consideration of the $\pi\rho\omega$ axial anomaly coupling, due to its relatively strong coupling strength which makes reaction mechanisms involving this vertex quite important. The effective Lagrangian density corresponding to this coupling can be written as

$$\mathcal{L}_{\pi\rho\omega} = \frac{g_{\pi\rho\omega}}{\sqrt{m_\rho m_\omega}} \varepsilon_{\alpha\beta\mu\nu} \partial_\mu \tilde{\rho}^\beta \cdot \partial_\nu \tilde{\pi}^\alpha \omega^\nu,$$  \hspace{1cm} (1)

where $\tilde{\rho}^\beta$, $\tilde{\pi}^\alpha$, and $\omega^\nu$ denote the $\rho$, $\pi$, and $\omega$ meson fields, respectively. The vector notation refers to the isospin space and $\varepsilon_{\alpha\beta\mu\nu}$ denotes the Levi-Civita antisymmetric tensor, with the convention $\varepsilon_{0123} = -1$. $m_\rho$ and $m_\omega$ denote the $\rho$ and $\omega$ mass, respectively, and $g_{\pi\rho\omega}$ stands for the corresponding (dimensionless) coupling constant.

A direct experimental access to the coupling constant of this anomalous vertex, $g_{\pi\rho\omega}$, is not possible because the decay $\omega \to \rho\pi\pi$ is energetically forbidden. Moreover, in addition to the determination of its magnitude, there is the problem of fixing its sign. The present work addresses the latter issue. In particular, we shall show that the relative sign of this coupling constant can be inferred most reliably from $\omega$-meson production processes in nucleon-nucleon ($NN$) collisions.

In many cases, the coupling constant $g_{\pi\rho\omega}$ is extracted in a purely phenomenological way, e.g., from the radiative decay $\omega \to \pi^0\gamma$, in conjunction with the vector meson dominance (VMD) assumption [1]. In this case, the sign of the $\pi\rho\omega$ coupling constant is related to the associated sign of the $\pi\omega\gamma$ coupling constant which, in turn, may be determined, e.g., from the relevant meson photoproduction processes by examining the interference effects between the relevant production mechanisms [2].

Indeed, the Jülich [3] and the Gießen [4, 5] groups, in their coupled-channel models of meson-nucleon reactions, use the sign of $g_{\pi\rho\omega}$ in Eq. (1) to be positive, consistent with the sign $g_{\pi\rho\omega}$ employed in pion photoproduction analyses [2, 4, 7, 8] as well as in the studies of deuteron electromagnetic form factors [9]. The coupled-channel model of the Gießen group includes also the $\gamma N$ channel. On the other hand, the earlier model of the Jülich group [10] used a negative value of the coupling constant $g_{\pi\rho\omega}$. Also, in Ref. [11], the reaction $pp \to pp\pi^0$ near threshold has been investigated using a negative value for $g_{\pi\rho\omega}$. The contribution of the production mechanism involving the $\pi\rho\omega$ coupling to this reaction is, however, rather small in the near-threshold-energy region. In Ref. [12], the coupling constant $g_{\pi\rho\omega}$ has been extracted from the study of the vector meson decay processes into three pions. There, a negative sign has been adopted for this coupling although, strictly speaking, only the relative sign between the coupling constants associated with the direct ($V \to 3\pi$) and the two-step process ($V \to \pi\rho \to 3\pi$) can be determined ($V = \omega, \phi$).

The difficulty of determining the sign of $g_{\pi\rho\omega}$ is demonstrated in Fig. 1, which shows the results of a tree-level calculation of the total and differential cross sections for the reaction $\pi^- p \to \omega n$ using both the positive and negative coupling values, $g_{\pi\rho\omega} = \pm 11.6$. The model includes nucleonic, mesonic as well as resonance currents. Details of the calculation will be reported elsewhere [14]. As can be seen, the results in Fig. 1 are qualitatively the same for both choices of the sign and illustrate that this reaction is unsuited for establishing the sign of $g_{\pi\rho\omega}$, at least in the energy domain where data exist. It should be noted that, although both choices of the sign yield similar results, the corresponding model parameter values, which were adjusted for each choice of the sign to reproduce roughly the data, are quite different. It is then clear that the ambiguity in the sign of $g_{\pi\rho\omega}$ introduces also uncertainties in the extracted resonance parameters. In particular, some resonance coupling constants change their magnitude by a factor of 1.5 and some couplings also change their signs depending on the sign choice of $g_{\pi\rho\omega}$. This evidently shows the importance of knowing

1 Some authors use the convention $\varepsilon_{0123} = +1$ (or, equivalently, $\varepsilon_{0123} = -1$), which is opposite to ours. In the current discussion, those have been converted to the present convention. Some other authors do not provide information on their phase conventions explicitly, which makes it difficult to find out the actual relative sign associated with their $\pi\rho\omega$ couplings.
the correct sign of $g_{\pi\rho\omega}$ for investigating the properties of nucleon resonances.

From a more theoretical point of view, the $\pi\rho\omega$ coupling has been considered within an effective chiral Lagrangian approach for vector mesons, where the anomalous $\pi\rho\omega$ coupling follows from the Bardeen-subtracted Wess-Zumino anomalous action. This approach recovers the result of the low-energy theorem in current algebra associated with the Adler-Bell-Jackiw anomaly. The details are reviewed by Meißner in Ref. [18]. (See also Ref. [19].) The corresponding coupling constant $g_{\pi\rho\omega}$ is given by

$$-\frac{g_{\pi\rho\omega}}{\sqrt{m_\rho m_\omega}} = \frac{3g^2}{8\pi^2 f_\pi},$$

where $f_\pi$ denotes the pion decay constant and $g$ is the universal gauge coupling constant. According to this result, the sign of $g_{\pi\rho\omega}$ is manifestly negative. However, the specific form of the $\pi\rho\omega$ coupling in Ref. [18] assumes a particular realization of VMD which is not mandatory. In fact, Jain et al. [20] have given an alternative derivation of the $\pi\rho\omega$ coupling arguing that the consideration of electromagnetic processes is not theoretically reliable for extracting $g_{\pi\rho\omega}$. In that derivation, the sign of $g_{\pi\rho\omega}$ is undetermined.

It is, therefore, clear that the sign of $g_{\pi\rho\omega}$ still remains to be determined and that the existing data on reaction processes such as $\pi^- p \to \omega n$ and $pp \to pp\pi^0$ do not impose sufficiently stringent constraints for determining this sign. In this paper, we show that $\omega$-meson production in $NN$ collisions, and specifically the reaction $pp \to pp\omega$, is more suited for the determination of the relative sign of $g_{\pi\rho\omega}$ and that the recent data from the COSY-TOF [21, 22] and COSY-ANKE [23, 24] collaborations in conjunction with the earlier data [25, 26] strongly favor a negative $g_{\pi\rho\omega}$, in contrast to a positive $g_{\pi\rho\omega}$ used in many calculations of pertinent hadronic reactions.

We follow the Distorted Wave Born Approximation approach employed in Refs. [27, 28, 29] in order to describe $\omega$-meson production in $NN$ collisions. The total amplitude $M^\mu$ is written as

$$M^\mu = (1 + T J^\mu(1 + G T_i)),$$

where $T_\lambda$ stands for the $NN$ initial and final state interactions as $\lambda = i$ and $f$, respectively. $G_\lambda$ denotes the corresponding two-body $NN$ propagator and $J^\mu$ denotes the $\omega$-meson production current. The $NN$ final state interaction (FSI), which is known to introduce strong energy dependence in this reaction near threshold, is treated exactly, while the initial state interaction (ISI) is considered within the on-shell approximation. We refer to Ref. [30] for the discussion on the validity of the latter approximation. Also, the effect of the finite $\omega$ meson width is

$$\Gamma_\omega = \frac{\alpha}{3\pi m_\omega^3} f_\pi^2.$$

FIG. 1: Results obtained in the tree-level approximation for $\pi^- p \to \omega n$ [14], using $g_{\pi\rho\omega} = +11.6$ (dashed curve) and $g_{\pi\rho\omega} = -11.6$ (solid curve) in Eq. (4). In each case the model parameter values were adjusted to reproduce roughly the data. Left panel: total cross section as a function of the total energy $W$. Right panel: $\omega$-meson angular distribution in the center-of-mass frame of the system. Data are from Refs. [15, 16, 17].

FIG. 2: The basic vector-meson production current $J_\mu$. (a) corresponds to the nucleonic current ($M = \sigma, a_0, \eta, \pi, \omega, \rho$), while (b) is the mesonic current. $V$ stands for the vector-meson $\omega$. 
taken into account in the present work. This effect is well known to enhance the cross sections near the threshold energies \cite{26,28,29}. When the final $NN$ state is a bound state, i.e., a deuteron, the reaction amplitude $M^\mu$ is calculated using the corresponding deuteron wave function as has been done in Ref. \cite{31}. We consider the nucleonic and mesonic currents as specified in Eq. (4) and by the Lagrangian densities (1) for the mesonic current and by

$$\mathcal{L}_{NN\omega} = -g_{NN\omega} \bar{\Psi} \left\{ \left( \gamma_\mu - \frac{\kappa_\omega}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \omega^\mu \right\} \Psi \quad (4)$$

for the nucleonic current. In the above equation, $\Psi$ stands for the nucleon field and $m_N$ for the nucleon mass. $g_{NN\omega}$ denotes the vector coupling constant and $\kappa_\omega$ is the ratio of the tensor to vector coupling constants. As far as the relative sign between the nucleonic and mesonic currents is concerned, we also need to specify the $NN\pi$ and $NN\rho$ vertices entering in the mesonic current. They are obtained from the Lagrangian densities

$$\mathcal{L}_{NN\rho} = -g_{NN\rho} \bar{\Psi} \left\{ \left( \gamma_\mu - \frac{\kappa_\rho}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \tilde{\tau} \cdot \tilde{\rho} \right\} \Psi ,$$

$$\mathcal{L}_{NN\pi} = -\frac{g_{NN\pi}}{2m_N} \bar{\Psi} \gamma_5 \gamma_\mu \tilde{\tau} \cdot \left( \partial^\mu \tilde{\pi} \right) \Psi ,$$

where $g_{NN\rho} = 3.36$, $\kappa_\rho = 6.1$ and $g_{NN\pi} = 13.45$.

Figure 3 shows our results for the total cross sections for $pp \rightarrow pp\omega$ and for $pn \rightarrow d\omega$, as well as the $\omega$ angular distribution in $pp \rightarrow pp\omega$. The free parameters of our model — the cutoff masses of the form factors at the $NN\omega$ and $\pi\rho\omega$ vertices, $\Lambda_N$ and $\Lambda_M$, respectively, (see Ref. \cite{29} for details) and the ratio of the tensor to vector coupling constant, $\kappa_\omega$, in Eq. (4) — were adjusted to reproduce the total and differential cross section data for $pp \rightarrow pp\omega$ at $Q = 173$ MeV. In doing so, we include the $NN$ ISI and FSI. The resulting parameter values are $\Lambda_N = 1200$ MeV, $\Lambda_M = 1120$ MeV and $\kappa_\omega = -2$. Here, a somewhat large value of $|\kappa_\omega|$ is required to reproduce the shape of the measured angular distribution at $Q = 173$ MeV. It can be brought down to a more reasonable value of $\kappa_\omega \sim -0.5$ once the resonance currents are considered as pointed out in Ref. \cite{24}. In this context we mention that the value of $\kappa_\omega$ influences the energy dependence of the total cross section too. In fact, for vanishing $\kappa_\omega$ the predicted energy dependence of the total cross section for $pp \rightarrow pp\omega$ is considerably better than that shown in Fig. 3(b). However, with such a value, a satisfactory description of the measured angular distributions is no longer possible.

The result for the $pn \rightarrow d\omega$ reaction (Fig. 3(b)) was obtained with the same model parameters as used for $pp \rightarrow pp\omega$. In addition, we assumed that the ISI causes the same reduction of the total cross section as it does in...
the $pp$-induced reaction. We should mention, however, that the validity of this assumption is debatable. Indeed, the experimental information on the $pn$ interaction for laboratory energies relevant for $\omega$ production whose threshold-energy is at around $T_{lab} = 1.89$ GeV is rather poor. Specifically, for $T = 0$ there is no $NN$ phase-shift analysis available for energies above $T_{lab} = 1.3$ GeV. At the latter energy, the reduction factor due to the ISI, evaluated according to the prescription given in Ref. [30], is about 0.3. On the other hand, the corresponding reduction factor for $pp \rightarrow pp\omega$ ($T = 1$) at $T_{lab} = 1.89$ GeV is about 0.45. These values may provide a very rough idea on the uncertainty associated with the present procedure to account for the $pn$ ISI. However, in view of the large error bars of the $pn \rightarrow d\omega$ data the mentioned ambiguities in the ISI are not really significant and one can certainly say that our model results for the $pn$ induced reaction are in line with the experimental data.

The results in Fig. 3 were obtained with the values of the coupling constants $g_{NN\omega} = 9$ and $g_{pp\omega} = +10$, which lead to a strong destructive interference between the nucleonic and mesonic current contributions, especially at lower excess energies in $pp \rightarrow pp\omega$. The value of $g_{pp\omega} = +10$ has been extracted from the measured $\omega \rightarrow \pi^0\gamma$ radiative decay rate in conjunction with the VMD assumption. The sign of this coupling constant is determined by the sign of the $\pi\omega\gamma$ coupling constant which, in turn, has been fixed from the analysis of pion photoproduction in the 1 GeV energy region [2]. As a consequence of this interference pattern, the predicted energy dependence of the total cross section for $pp \rightarrow pp\omega$ is in serious disagreement with the experimental information. Specifically, the model calculation (with parameters adjusted to the data at higher energies) strongly underestimates the data at near-threshold energies. We note that other authors who have investigated $\omega$-meson production in $NN$ collisions [32, 33] have used the same relative sign between the nucleonic and mesonic currents as in Refs. [27, 28, 29].

A possible mechanism to cure the discrepancy observed above is the excitation of nucleon resonances. In fact, in Ref. [29] nucleon resonance contributions have been explored in $pp \rightarrow pp\omega$; however, these were found to be insufficient to provide the necessary enhancement of the total cross section near threshold in order to reproduce the data. Another possibility to remedy the problem is the (background) $\omega N$ FSI. In the case of $\eta$ production in $NN$ collisions, it is generally believed that the $\eta N$ FSI is responsible for the experimentally observed enhancement of the cross section near threshold by a factor of two or so. Only its actual strength is still under debate as reflected by the values of the $\eta N$ scattering length one can find in the literature: $a_{\eta N} = (0.2 \sim 1.1, 0.26 \sim 0.35)$ fm [34]. In comparison, the estimated (spin-averaged) $\omega N$ scattering length is of the order of $a_{\omega N} = (-0.026 \sim 1.6, 0.20 \sim 0.30)$ fm [4, 33, 30]. Therefore, one might expect also some effects of the $\omega N$ FSI in $pp \rightarrow pp\omega$. However, in any case, it is not trivial to come up with new mechanisms which could enhance the $pp \rightarrow pp\omega$ cross section close to threshold by more than an order of magnitude and, at the same time, leave the cross section in $pn \rightarrow d\omega$ more or less unchanged in order to solve the observed discrepancies.

In the following, we show that the discrepancy discussed above can be largely eliminated if one changes the sign of the $\pi\rho\omega$ coupling constant with respect to the $NN\omega$ coupling constant, i.e., if one assumes a negative coupling constant $g_{\pi\rho\omega}$ in Eq. (1). The change of the sign is motivated by the following two observations. First, we note that the isospin operator structures in the nucleonic current are $1$ for the isoscalar meson exchanges ($M = \sigma, \eta, \omega$) and $\bar{t}_1 \cdot \bar{t}_2$ for the isovector meson exchanges ($M = \alpha, \pi, \rho$). The structure of the mesonic current is $\bar{t}_1 \cdot \bar{t}_2$, i.e., the same as that for the isovector meson exchanges in the nucleonic current. The isospin matrix element is then $1$ for $pp \rightarrow pp\omega$ (total isospin $T = 1$) and $-3$ for $pn \rightarrow d\omega$ ($T = 0$) in the mesonic current and in the part of the nucleonic current involving isovector meson exchanges, while it is always $1$ in the nucleonic current involving the isoscalar meson exchanges. Second, the qualitative features of the calculated total cross sections close to the threshold displayed in Figs. 3(a,b) can be understood easily if one assumes that the reaction amplitudes (without the isoscalar factor) due to the isoscalar (isovector) meson exchanges in the nucleonic current, $\alpha$ ($\beta$), and due to the mesonic current, $\gamma$, are related by $\alpha \sim -2c/3, \beta \sim -c/3$ and $\gamma \sim c$, where $c$ is a complex number. We then have

$$M_{pp\omega} = \alpha + \beta + \gamma \sim 0,$$
$$M_{d\omega} = \alpha - 3\beta - 3\gamma \sim \frac{8}{3}c,$$  \hspace{1cm} (6)

for the $pp \rightarrow pp\omega$ and $pn \rightarrow d\omega$ total reaction amplitudes, $M_{pp\omega}$ and $M_{d\omega}$, respectively. Note, in particular, that the nucleonic and mesonic current contributions are practically the same in the $pp$-induced reaction, while in the $pn$-induced reaction, the mesonic current dominates over the nucleonic current. Moreover, in the latter reaction, the total current contribution is smaller than the mesonic and larger than the nucleonic current contributions. If we now change the sign of the mesonic current, we have

$$M_{pp\omega} = \alpha + \beta - \gamma \sim -2c,$$
$$M_{d\omega} = \alpha - 3\beta + 3\gamma \sim \frac{10}{3}c,$$  \hspace{1cm} (7)

for the corresponding total reaction amplitudes. This seems precisely what is required to reproduce the measured cross sections in Figs. 3(a,b): an enhancement of

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2 Here, the term destructive or constructive interference will be employed in the sense of the resulting cross section being smaller or larger than the sum of the individual contributions.
the total cross section close to threshold in $pp \rightarrow pp\omega$ and practically no change in $pn \rightarrow d\omega$.

In Fig. 4 our results with $g_{NN\omega} = 9$ and $g_{\pi\rho\omega} = -10$ are displayed. We follow the same strategy for adjusting the model parameters as described above for the case of a positive $\pi\rho\omega$ coupling constant. Now the resulting parameter values are $\Lambda_N = 1100$ MeV, $\Lambda_M = 1000$ MeV, and $\kappa_\omega = -2$. As can be seen, in contrast to the predictions in Fig. 3 for $g_{\pi\rho\omega} = +10$, with the negative sign the total cross section for $pp \rightarrow pp\omega$ is in much better agreement with the data. Specifically, the underestimation of the cross section near the threshold by more than an order of magnitude (cf. Fig. 3) is now strongly reduced to only a factor of about 1.5. At the same time the reaction $pn \rightarrow d\omega$ is again in qualitative agreement with the data (Fig. 3b). The dotted curves in Fig. 4 correspond to results with $\Lambda_N = 990$ MeV, $\Lambda_M = 950$ MeV, and $\kappa_\omega = 0$. Contrary to the case with positive $g_{\pi\rho\omega}$, where a value of about $\kappa_\omega = -2$ is required to reproduce the shape of the measured $\omega$ angular distribution, now, with a negative value of $g_{\pi\rho\omega}$, the existing data can be described rather reasonably even with a vanishing $\kappa_\omega$. Note that $\kappa_\omega \approx 0$ is more in line with the values employed in other reactions such as $NN$ scattering.

As discussed above, it is very reasonable to expect that nucleon resonances and (background) $\omega N$ FSI would bring the prediction in Fig. 4 in even better agreement with the data once they are taken into account together. Efforts to include them consistently with other more basic reactions such as $\pi N \rightarrow \omega N$ and $\gamma N \rightarrow \omega N$ are currently in progress.

In this context we want to emphasize that our results with the negative coupling constant $g_{\pi\rho\omega}$ are actually in line with the recent calculations presented in Ref. [37], once we neglect the effect of the $\omega$ meson width and use a constant reduction factor to simulate the $NN$ ISI instead of its explicit inclusion. As mentioned before, taking into account the $\omega$ meson width enhances the cross sections near threshold [26, 28, 29]. On the other hand, the explicit inclusion of the ISI in our investigation introduces a significant energy dependence over the energy range considered. If the model parameters are adjusted to reproduce the data at higher energies, as in our calculation, then one observes an underestimation of the total cross section close to threshold, (cf. Fig. 4a). Note that neither finite width effects nor the explicit inclusion of the $NN$ ISI were considered in Ref. [37].

In summary, we have shown that the relative sign of the $\pi\rho\omega$ coupling constant in Eq. (1) may be most sensitively determined from $\omega$ meson production in $NN$ collisions, due to the distinct isospin structures of the nucleonic and mesonic currents. Other hadronic reactions such as $\pi N \rightarrow \omega N$, where the isospin structure is the same for both the (corresponding) nucleonic and mesonic currents, are certainly much less suited for fixing the sign of the $\pi\rho\omega$ coupling constant.

Indeed, according to our results the existing data for $pp \rightarrow pp\omega$ strongly favor a negative sign of the coupling
Therefore, we expect that the sign of higher-mass nucleon resonance parameters from the data. Defining the non-resonant amplitudes for extracting the use of the correct sign of \( g_{\pi\rho\omega} \) and using the parameters of Ref. [8]. Hence, the calculation including only the Born term and \( \omega \)-exchange could be crucial in defining the non-resonant amplitudes for extracting the higher-mass nucleon resonance parameters from the data. However, the \( \omega \)-exchange mechanism becomes very large in the higher-mass nucleon resonance region. For example, changing the sign in the \( \omega \)-exchange current will not influence the main results of those studies too much, although it may help to remove some remaining discrepancies with the data. Therefore, we expect that the sign of \( g_{\pi\rho\omega} \) as fixed in this work will have an impact on the corresponding nucleon resonance parameters too.

Finally, we mention that the present result is, admittedly, model dependent. Indeed, our calculations are based on a model containing a few free parameters that have been adjusted to reproduce the data. However, we believe that our conclusion on the sign of \( g_{\pi\rho\omega} \) is rather robust, given the relatively strong effect of the interference between the nucleonic and mesonic currents on the energy dependence of the total cross sections. Although there are other possible production mechanisms ignored in the present calculation, their effects would not be strong enough to change our conclusion, as can be inferred from our knowledge in the study of meson production reactions in \( NN \) collisions.

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