Near-threshold $\omega$-meson production in proton-proton collisions

With or without resonance excitations?

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We present results for the $pp \rightarrow pp\omega$ reaction studied by considering two different scenarios: with and without the inclusion of nucleon resonance excitations. The recently measured angular distribution by the COSY-TOF Collaboration at an excess energy of $Q = 173$ MeV and the energy dependence of the total cross section data for $\pi^-p \rightarrow \omega n$ are used to calibrate the model parameters. The inclusion of nucleon resonances improves the theoretical prediction for the energy dependence of the total cross section in $pp \rightarrow pp\omega$ at excess energies $Q < 31$ MeV. However, it still underestimates the data by about a factor of two, and remains a problem in understanding the reaction mechanism.

1. Introduction

One of the reasons for a renewed interest in the $pp \rightarrow pp\omega$ reaction is the recently measured $\omega$ angular distribution by the COSY-TOF Collaboration [1] at an excess energy, $Q = 173$ MeV. In addition to the existing total cross section data from SATURNE [2] ($Q < 31$ MeV), the new data can be used to further constrain theoretical models. We study the $pp \rightarrow pp\omega$ reaction considering two different scenarios: with and without the inclusion of nucleon resonance excitations [3]. We use a relativistic hadronic model, where the reaction amplitude is calculated in DWBA which includes both the NN initial and final state interactions (denoted by ISI and FSI, respectively). The ISI is implemented in the on-shell approximation [4, 5], while FSI is generated using the Bonn NN potential [6]. Effects of the finite $\omega$ width are also included. The $\omega N$ FSI is accounted for only via the pole diagrams (s-channel processes). Most of the parameter values of the model are fixed from considerations of other reactions closely related to the one in the present study and are given in Ref. [5]. For further details of the model we refer to Ref. [5].

The $\omega$-meson production amplitude and its associated production currents, are depicted in Figs. 1 and 2 respectively. The production currents consist of, a) nucleonic (and/or resonance) current and b) mesonic current. In section 2, we discuss the results without the nucleon resonance degrees of freedom, while in section 3, we present the results with the resonance degrees of freedom.

2. Results without resonance excitations

One of the two free parameters in the nucleonic current, the tensor to vector coupling constant ratio, $\kappa_\omega \equiv f_\omega/g_\omega$, at the $\omega NN$ vertex is determined by fitting the angular distribution data at $Q = 173$ MeV [4]; the shape of the angular distribution is found to be quite sensitive to the value of $\kappa_\omega$ [4]. Also, the cutoff parameter, $\Lambda_N$, in the form

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Figure 1. Amplitude $M$ for $NN \to NN\omega$. $T_{MN}$ stands for meson nucleon $T$ matrix treated with an approximation [5].

Figure 2. $\omega$ ( = $V$) production currents, a) nucleonic (and/or resonance) current, where, $M = \pi, \eta, \rho, \omega, \sigma, a_0$, and b) mesonic current.

factor at the $\omega NN$ vertex is adjusted concomitantly to reproduce the total cross section at $Q = 173$ MeV. Using the value, $g_{\omega NN} = +9.0$, associated with the physical $\omega$ (not with the virtual $\omega$ exchanged), we obtain the value of $\kappa_\omega = -2.0$ to best reproduce the angular distribution as shown in Fig. 3 (left panel). (The value quoted in Ref. [7] should read $g_{\omega NN} = +9.0$.) The shape of the angular distribution is quite insensitive to the values of $g_{\omega NN}$, as shown in Fig. 3, where the result in the right panel is obtained by using a value of $(g_{\omega NN})^2/4\pi = (17.37)^2/4\pi = 24$, which corresponds approximately to the value used in the Bonn NN potential [8].

The energy dependence of the total cross section calculated using the values of $\kappa_\omega = -2.0$ and $g_{\omega NN} = +9.0$, is shown in Fig. 4 together with the result of Ref. [8] used in the analysis of the SATURNE data [2, 8]. The present result substantially underestimates the SATURNE data [4, 8] for $Q < 31$ MeV. The reason for this discrepancy is that, as we shall show later, we probably overestimate too much the mesonic current contribution at $Q = 173$ MeV. This results in substantial underestimation of the cross section at near threshold due to the much more efficient destructive interference between the nucleonic and mesonic current contributions as the excess energy decreases.

Although currently there is no definite experimental evidence of a $\omega$-meson coupling to a nucleon resonance, it would be natural to expect some resonance current contributions, especially at nucleon incident energies involved in the production of $\omega$ in NN collisions. The reduction of the mesonic current at high excess energies may then be compensated by the nucleon resonance current contribution. We discuss such a scenario next.

3. Results with resonance excitations

We now include nucleon resonance degrees of freedom (resonance current) in the model. The criteria for selecting relevant resonances are: (i) those appreciably decay to $N + \gamma$ to use the vector meson dominance assumption to produce the $\omega$, (ii) those mass distributions are around $(m_N + m_\omega)$, to be able to maximally contribute near threshold, (iii) select a minimum number of resonances to avoid introducing many new parameters, (iv) those that can describe consistently the $\pi^- p \to \omega n$ reaction. As a result, we have selected
resonances $S_{11}(1535), P_{11}(1710), D_{13}(1700)$ and $P_{13}(1720)$.

In Fig. 3 we show the calculated energy dependence of the total cross section for $p^{-}p \rightarrow \omega n$. We note that at the excess energy of $Q = 173$ MeV in $pp \rightarrow pp\omega$, the center-of-mass energy of the subsystem $p^{-}p \rightarrow \omega n$ will reach a maximum value of $W \simeq 1.9$ GeV. At lower $W$, $D_{13}(1700)$ and $P_{13}(1720)$ contributions are dominant, but not $S_{11}(1535)$ nor $P_{11}(1710)$. Also, without the inclusion of the resonances, it is very difficult to reproduce the near-threshold behavior of the $p^{-}p \rightarrow \omega n$ total cross section within a reasonable set of parameters. With the inclusion of the resonances, we need somewhat stronger form factor for the $\omega \rho \pi$ vertex. In particular, the part of the form factor which account for the off-shellness of the $\rho$ meson is of dipole form with the cutoff parameter $\Lambda_{\rho} = 850$ MeV [5]. A cutoff parameter value of $\Lambda_{N} = 1.1$ GeV was also determined at the $\omega NN$ vertex. In addition, because $P_{11}(1710)$ has an appreciable decay branch to $N + 2\pi$, we simulated this by a $\sigma$-meson, where the value for $g_{P_{11}N\sigma}$ is adjusted to reproduce the $pp \rightarrow pp\omega$ total cross section data at $Q = 173$ MeV. Thus, the contribution from $P_{11}(1710)$ should be regarded also as taking into account the other possible resonance contributions not included explicitly in our model. We obtained a value of $g_{P_{11}N\sigma} = -4.3$; results for another possible value, $g_{P_{11}N\sigma} = 4.8$, are not shown, because the calculated energy dependence of the total cross section is worse, although the angular distribution is better described at $Q = 173$ MeV. Here, the value of $\kappa_{\omega}$ was set to be $-0.5$, more in line with the estimates from other studies. With the value of $\kappa_{\omega} = -2.0$ obtained in the previous it would be very difficult to describe consistently the NN scattering data [8].

In Fig. 4 we show the calculated energy dependence of the total cross section for $pp \rightarrow pp\omega$. The result is greatly improved compared to that without the inclusion of any resonances in the previous section. However, it still underestimates the SATURNE data [2] ($Q < 31$ MeV) by about a factor of two. Fig. 5 shows the decomposition of the resonance contribution. At near threshold the dominant contribution comes from $D_{13}(1700)$, while at higher excess energy, the dominant contribution comes from $P_{11}(1710)$, which was negligible in $p^{-}p \rightarrow \omega n$. If we want to be consistent with both the $p^{-}p \rightarrow \omega n$ and $pp \rightarrow pp\omega$ reactions, it seems necessary to include at least $P_{11}(1710), D_{13}(1700)$ and $P_{13}(1720)$ resonances in the present approach.

Figure 3. Calculated angular distribution with no resonances. The left (right) panel is the best fit (result with the Bonn potential value for $g_{\omega NN}$).
4. Summary

We have reported our results for the $pp \rightarrow pp\omega$ reaction studied by considering two different scenarios: with and without the inclusion of nucleon resonance excitations. The results show that the energy dependence of the total cross section $Q < 173$ MeV is apparently better described by the inclusion of resonance excitations, which is also consistent with the $\pi^- p \rightarrow \omega n$ reaction. However, it still underestimates the data in the $Q < 31$ MeV region by about a factor of two, and remains a problem in understanding the reaction mechanism.

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