Near-threshold production of $\omega$ mesons in the $pn \to d\omega$ reaction

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Abstract. The first measurement of the $pn \to d\omega$ total cross section has been achieved at mean excess energies of $Q \approx 28$ and 57 MeV by using a deuterium cluster-jet target. The momentum of the fast deuteron was measured in the ANKE spectrometer at COSY-Jülich and that of the slow “spectator” proton ($p_{sp}$) from the $pd \to p_{sp}d\omega$ reaction in a silicon telescope placed close to the target. The cross sections lie above those measured for $pp \to pp\omega$ but seem to be below theoretical predictions.

PACS. 25.40.Ve Other reactions above meson production thresholds (Energies $> 400$ MeV) – 25.40.Fq Inelastic neutron scattering – 14.40.Cs Other mesons with $Q < 140$ MeV

1 Introduction

The last few years have seen several measurements of $\eta$ production in nucleon-nucleon collisions [1], but relatively few of $\omega$ production [2,3]. The S-wave amplitude in the $\eta$ case is strong and the total $pp \to pp\eta$ cross section largely follows phase space modified by the $pp$ final state interaction up to an excess energy $Q = \sqrt{s} - \sum p_f \approx 60$ MeV, though there is some evidence for an $\eta pp$ final state enhancement at very low $Q$ [4]. Here $s$ is the total centre-of-mass (cm) energy and $p_f$ are the masses of the particles in the final state. Quasi-free $\eta$ production in proton-neutron collisions has been measured by detecting the photons from $\eta$ decay and it is found that for $Q < 100$ MeV the cross section ratio $R = \sigma_{\text{tot}}(pn \to pnn) / \sigma_{\text{tot}}(pp \to pp\eta)$ is larger than for $pp \to pp\eta$ [4], and this can be understood quantitatively in terms of phase space in a largely model-independent way [4]. In all meson production reactions it is important to have data on the different possible isospin combinations in order to constrain theoretical models. It is therefore interesting to see whether a similar isospin dependence is found for the $\omega$, the next heavier isoscalar meson.

Unlike the $\eta$ case, the $\omega$-meson has a significant width (8.4 MeV/$c^2$) and so $Q$ is here defined with respect to the central mass value of 782.6 MeV/$c^2$ [5]. The $pp \to pp\omega$ total cross section has been measured at five energies in the range $4 < Q \leq 30$ MeV at the SATURNE SPESIII spectrometer [2] and at $Q = 92$ MeV at COSY-TOF [6] where, in both cases, the $\omega$ was identified through the missing mass technique. The energy dependence deduced is rather similar to that of the $\eta$, except that the phase space and $pp$ final state interaction have to be smeared over the finite $\omega$ width, a feature which becomes important close to the nominal threshold [2].

Attempts to measure the $np \to d\omega$ reaction using a neutron beam are complicated by the intrinsic momentum spread, which is typically 7% FWHM even for a stripped deuteron beam [7]. The alternative is to use a deuterium target and effectively measure the momentum of the struck neutron. This is made possible by detecting the very low momentum recoil protons, $\lesssim 200$ MeV/$c$, in the $pd \to p_{sp}d\omega$ reaction in a silicon telescope placed close to the target. Such an approach is feasible at internal experiments at storage rings such as CELSIUS or COSY because of the thin windowless targets that can be used there. Under these conditions the recoil proton can be...
largely treated as a “spectator” that only enters the reaction through its modification of the kinematics. The measurement of the fast deuteron in coincidence would then allow us to identify the ω by the missing mass method. By varying the angle and momentum of the spectator proton it is possible to change the value of Q while keeping the beam momentum fixed. The principle of this method has been proved at CELSIUS for the pn → dπ⁰ reaction, where Q could be determined to 2 MeV.

2 Experimental Set-up

Our experiment was performed using a deuterium cluster-jet target at the ANKE spectrometer situated inside the COoler SYnchrotron COSY-Jülich, with the fast deuteron being measured in the ANKE Forward Detector and the spectator proton in solid state counters. The silicon telescope used for this purpose is described in detail in Ref. [12] and only the principal features will be mentioned here. The three silicon layers indicated in Fig. 1 of respectively 60 µm, 300 µm, and 5 mm, covered polar angles 83° < θsp < 104° and ±7° in azimuth. Protons with kinetic energies Tsp in the range 2–6 MeV traversed the first layer but were stopped in the second, while those in the range 6–30 MeV were stopped rather in the final thick layer. Energy resolution of the order of σ = 150 keV was obtained. The second and third layers were composed of strips arranged perpendicular to the beam such that for Tsp > 8 MeV a resolution of σ(θsp) ≤ 5° could be achieved. For the lower energy protons, neglecting the small non-target background, the finite target size led to σ(θsp) ≤ 5°.

There was no difficulty in separating slow deuterons from protons via the E − ∆E method in two ranges: 2.6 < Tsp < 4.4 MeV (70 < psp < 91 MeV/c) and also 8 < Tsp < 22 MeV (123 < psp < 204 MeV/c). This is illustrated for the lower range in Fig. 2. It is seen here that, by choosing the 4.4 MeV upper limit, one avoids the possibility of misidentifying deuterons traversing the first two layers but missing the third.

The ability to identify a deuteron in the telescope in coincidence with a proton in the forward detector also allows us to obtain simultaneously the luminosity by measuring proton-deuteron elastic scattering through a determination of the deuteron kinetic energy. For this purpose we have calculated the elastic proton-deuteron cross section normalisation. The overall systematic luminosity error used to determine absolute cross sections was thus taken to be 20%. It should be noted, however, that the error in the relative normalisation between different beam energies is at most 5%.

In order to distinguish deuterons with momenta around 2 GeV/c, arising from the pd → pspdω reaction, from a
proton background that is two orders of magnitude higher, inclined Čerenkov counters were installed behind the multiwire proportional chambers and scintillator hodoscope of the forward detection system of ANKE [11,15]. To understand the detection principle, consider the detector response for a proton and deuteron with the same momentum. The opening angle of the Čerenkov light cone for the faster proton is larger. Thus part of the light can reach the photomultiplier after being totally reflected in the counter, whereas all the light produced by the deuteron leaves the counter. A momentum-dependent threshold was applied so as not to change the differential distributions.

The hodoscope, consisting of two layers of scintillation counters, provides an additional criterion for the deuteron identification using the energy loss in both layers. By simultaneously varying the $\Delta E$-cut and Čerenkov efficiency level, an optimal combination was found which leads to only a 20% loss of deuterons while giving a 92% suppression of protons due to the Čerenkov counters alone. Projecting the energy loss in the second layer along the predicted energy loss of deuterons ($\propto \beta_d^{-2}$), one obtains the dotted histogram shown in Fig. 3. A further cut on the analogous distribution in the first layer reveals a clear deuteron peak (solid line). Moreover, the shape of the remaining proton background can be determined using the energy loss distribution of suppressed particles which, after scaling, is drawn as the dashed line. This shows that the proton background is on the 10% level.

### 3 Data Analysis

Having identified a spectator proton in the telescope and a deuteron in the forward array and furthermore measured their momenta and directions, one can evaluate the missing mass $m_X$ in the reaction. To clarify the effects of the kinematics, it is sufficient to treat the spectator as being non-relativistic. To order $p_{sp}^2$, we have then

$$m_X^2 \approx \tilde{m}_X^2 + 2(p_d - p) \cdot p_{sp} - 2 \frac{(E + m_d - E_d)}{m_p} p_{sp}^2, \quad (1)$$

where $\tilde{m}_X$ is the value obtained at $p_{sp} = 0$. Here $p$ and $E$ are the laboratory momentum and total energy of the incident proton, $p_d$ and $E_d$ those of the produced deuteron, and $m_d$ and $m_p$ the masses of the deuteron and proton respectively. The square of the $pn$ cm energy, $s$, can be evaluated purely using measurements in the spectator counter and from this $Q$ can be derived:

$$s = (m_d + m_\omega + Q)^2 \approx \bar{s} + 2p_{sp}\cos \theta_{sp} - \left(\frac{E + m_d}{m_p}\right)p_{sp}^2, \quad (2)$$

where $\bar{s}$ is the value for a stationary neutron. Because the telescope is placed around $\theta_{sp} \approx 90^\circ$, $\partial s/\partial \theta_{sp}$ is then maximal and so the value of $Q$ depends sensitively upon the determination of the polar angle of the spectator with respect to the beam direction.

Since in our set-up the fast deuteron is measured near the forward direction, the same sort of sensitivity is also found for $m_X$ when using Eq. (1). Now for each beam momentum the beam direction could not be established to much better than 0.1°, and this may induce a systematic shift of a few MeV/c² in the value of $m_X$. On the other hand, in view of the $\omega$ width, the uncertainty in the beam momentum ($< 1$ MeV/c) is unimportant for both $Q$ and $m_X$ at this level of accuracy. The struck neutron is slightly off its mass shell but the off-shellness is controlled by the spectator momentum and rests small throughout our experiment.

In Fig. 4 we show our results from the first two silicon layers ($70 < p_{sp} < 91$ MeV/c), where the spectator hypothesis should be very good. The angular information is important for the missing mass determination but, in view of the limited statistics, we had to sum over rather wide bins in excess energy. Experience with $\omega$ production in proton-proton collisions shows that there is considerable multi-pion production under the $\omega$ peak [2]. Without measuring the products of the $\omega$ decay, this can only be reliably estimated by comparing data above and below the $\omega$ threshold. Two of the four momenta correspond to largely below-threshold measurements and two above, at mean values of $Q$ equal to about 28 and 57 MeV.

There is an indication of a weak $\omega$ signal at the highest energy and, in order to evaluate its significance, we have to master the large multipion background over our range of energies. Two different approaches have been undertaken to overcome this problem. In the first, pion production is modelled within a phase-space Monte Carlo description.
The second method is identical to that used in the analysis of the $pp \rightarrow pp\omega$ experiment [2], where the data below $\omega$ threshold were taken to be representative of the background above, being merely shifted kinematically due to the changed beam energy such that the upper edges of phase space match. This matching of the ends of phase space can also be used to check the set-up of the system at each momentum. The only significant discrepancy was found at 2.807 GeV/c where, in order to account for a slight displacement observed in the data, 3 MeV/c$^2$ has been subtracted from all $m_X$ values at this beam momentum. As will be shown in the next section, the two different analysis methodologies give consistent results within the error bars.

Most of the background can be described by phase space convoluted with the ANKE acceptance, which provides a severe cut at low $m_X$. It should be noted that the available $np \rightarrow d\pi^+\pi^-$ data in our energy range show the deuteron distribution to be fairly isotropic in the cm system [16]. In the absence of neutron data, we parameterised the deuteron distribution to be fairly isotropic in the cm system.

In proton-proton collisions by deuteron [16], where

$$\sigma(s) = A \left(1 - \frac{s_0}{s}\right)^{p_1} \left(\frac{s_0}{s}\right)^{p_2},$$

where $s_0$ is the threshold for $N\pi$ production. The exponent $p_1$ is fixed by phase space, but $A$ and $p_2$ are free parameters adjusted to reproduce the $pp \rightarrow d(N\pi)$ data for 2, 3 and 4 pion production [17]. The assumption that each of the three contributions follows a $(N + 1)$-body phase space, undistorted by $\Delta$ or $\rho$ resonances, gives a description of the $m_X$ distributions for different beam energies. To model the $pn \rightarrow d(N\pi)$ background, the energy dependence from the pp case has been used to fix the $p_1$, with the $A$ being adjusted to reproduce simultaneously our experimental distribution at 2.7 GeV/c and the phase-space maximum at 2.9 GeV/c. The relative normalisation between these two momenta was determined from the pd elastic scattering data. The adjusted $A$ values, together with the relative normalisation established from the luminosity measurement, were used to describe the multipion background at 2.6 GeV/c and at 2.8 GeV/c, as shown in Fig. 4.

Our method gives a plausible description of the background under the $\omega$ peak at $Q \approx 57$ MeV but any $\omega$ signal at $Q \approx 28$ MeV lies close to the maximum of the phase-space acceptance and the evaluation of its strength depends much more critically upon the background assumptions. Nevertheless, within the parametrisation of Eq. (3), it is impossible to describe the phase-space maxima simultaneously at the four energies in Fig. 4 without invoking some $\omega$ signal at $Q \approx 28$ MeV.

To describe the $\omega$ contribution to the missing mass spectra, we take the $pm \rightarrow d\omega$ matrix element to be constant over the $Q$-bin so that the cross section follows phase space. This, combined with the decrease of acceptance at large $Q$, means that the mean value of $Q$ is not quite at the centre of the bin. Other plausible assumptions, such as a constant cross section, would lead to negligible changes in the evaluation of the cross section and mean value of $Q$. In the simulation of the $pd \rightarrow p_{\omega}dX$ reaction, the cross section is smeared over the Fermi motion in the deuteron using the PLUTO event generator [18]. This employs the Hamada-Johnston wave function [19] though, at these small values of spectator momenta, other more realistic wave functions give indistinguishable results. The same event generator is used also for the multipion background.

Turning now to our second approach, the authors of ref. [2] noticed that, apart from the $\omega$ signal, the shape of the $pp \rightarrow pp X$ missing mass spectrum varied little with beam energy provided that one looked at the distribution...
with respect to the maximum missing mass. More quantitatively, if \( \beta \) and \( \beta_m \) are c.m. velocities at energies \( T \) and \( T_m \) respectively, the measured momenta and angles of the protons were first transformed, event-by-event, from the laboratory to the c.m. system with the velocity \(-\beta\) and then transformed back to the laboratory with the velocity \(+\beta_m\). To see to what extent this approach is valid for the ANKE spectrometer, which has a much smaller overall acceptance than that of SPESIII, we have reconstructed the missing mass for the copious proton production \( pd \rightarrow p_{sp}pX \). The data at the four different beam momenta, kinematically shifted to 2.9 GeV/c and normalised to the same total number of events, are shown in Fig. 5.

![Fig. 5. Missing-mass spectra of the \( pd \rightarrow p_{sp}pX \) reaction at 2.6 (crosses), 2.7 (stars), 2.8 (closed circles), and 2.9 GeV/c (open circles) kinematically shifted using the SPESIII procedure. The data are all normalised to the same total of 100%.](image)

It is clear from the figure that for \( m_X > 1.4 \) GeV/c\(^2\) the shifted data are in mutual agreement at all beam momenta. For lower missing masses one sees the effect of the production of the \( \Delta(1232) \) isobar, whose position in the shifted mass scale depends, of course, upon the beam momentum. The figure also nicely illustrates the influence of the ANKE acceptance cut, which strongly favours events close to the maximum missing mass.

When the identical analysis procedure is applied to the \( pd \rightarrow p_{sp}dX \) data, the backgrounds away from the \( \omega \) peak at the different momenta are again found to be completely consistent. An average background could therefore be reconstructed and this is shown for the two above-threshold momenta in Fig. 6. The differences between the experimental data and constructed background shows evidence for structure in the \( \omega \) region and these have been fitted to \( \omega \) peaks whose widths were fixed by the Monte Carlo simulation. The \( \omega \) masses obtained from the fits at the two momenta, 780 \( \pm \) 8 and 787 \( \pm \) 4 MeV/c\(^2\), do not differ significantly from the expected value.

4 Results

By comparing the residual signal in Fig. 3 with a simulation of \( \omega \) production over this range of spectator energies and angles, we would conclude from simulated background model that \( \sigma_{tot}(pn \rightarrow d\omega) = (2.9 \pm 0.8 \) \( \mu \)b at \( Q = (28^{+16}_{-20}) \) MeV and \( (8.5 \pm 2.8) \) \( \mu \)b at \( Q = (57^{+21}_{-15}) \) MeV, where the uncertainty in \( Q \) reflects the total width of the bin and only the statistical error in the cross section is quoted. The corresponding numbers obtained using the SPESIII background technique, \( (2.2 \pm 1.4) \) \( \mu \)b and \( (9.4 \pm 3.3) \) \( \mu \)b respectively, are consistent with the first method, though the statistical errors are larger because we had to subtract a background with limited statistics. This contrasts with our first approach where we imposed the condition that the background should be smooth. Averaging the two sets of results, we obtain \( \sigma_{tot} = (2.6 \pm 1.6 \pm 2.3) \) \( \mu \)b and \( (9.0 \pm 3.2^{+5.5}_{-2.0}) \) \( \mu \)b at the two excess energies. The second, systematic, error bar includes some contribution arising from the ambiguity of the background discussed above but others, such as the uncertainty in the luminosity, are common to both the signal and background.

In view of the limited statistics it might be helpful to quote upper limits resulting from the fits to the count differences shown in Fig. 3. At the 90% confidence level the cross sections at 2.8 and 2.9 GeV/c are below \( (7.5 \pm 5) \) \( \mu \)b...
and \((17 \pm 6) \mu b\) respectively, where the second figure is the rescaled systematic uncertainty.

One source of systematic uncertainty comes from the restricted angular acceptance of ANKE [11], a problem that becomes more serious with increasing \(Q\). The simulation of the acceptance, illustrated in Fig. 7 for an isotropic production distribution, shows that, while the distribution is fairly flat at 2.8 GeV/c, few events would be accepted close to 90° at 2.9 GeV/c. Although at our energies we might expect \(S\)-wave production to dominate, when this acceptance is weighted with the possible pure \(P\)-wave angular variations of \(\cos^2 \theta\) or \(\sin^2 \theta\), the resulting overall acceptance estimate at 2.9 GeV/c is changed by factors of 1.7 and 0.65 respectively. These are, however, extreme scenarios and a systematic error of half of the difference of 1.7 and 0.65 respectively. These are, however, extreme scenarios and a systematic error of half of the difference between these values is a generous estimate of this uncertainty. In more refined experiments, where the statistics for spectators in the higher range, 8 < \(T_{sp}\) < 22 MeV, are only about a third of those in the lower range. Nevertheless, the corresponding missing mass spectra are consistent with those shown for the lower spectator energies in Fig. 4 with \(\omega\) cross sections compatible with our analysis, we find \(\sigma_{tot}(pn \rightarrow pn\omega) / \sigma_{tot}(pp \rightarrow \omega) = 5\). This would explain most of the 6.5 factor found in the \(\eta\) case [6]. Assuming that the ratio \(d\omega\) to \(pp\omega\) is as for \(\eta\) production, the parametrisation of the available \(pp \rightarrow pp\omega\) data [21] leads to the solid curve, which lies about a factor of three above our data. Another estimate is a little lower but similar in shape [23]. Both curves lie within the extremes of the predictions of the Jülich theory group [24], where the major uncertainty arises from the relative strengths of production and exchange current terms.

\[ \sigma_{tot}(pd \rightarrow pd\omega) = (1.6 \pm 0.3) \text{mb} \]

Fig. 7. Predicted angular acceptance for \(pd \rightarrow pd\omega\) events at 2.9 GeV/c (solid line) as a function of the deuteron c.m. angle, assuming an isotropic production process. At 2.8 GeV/c (dashed line) the distribution becomes more uniform.

5 Conclusions

In any meson exchange model, the relative strength of \(\omega\) production in \(pp\) and \(pn\) collisions depends sensitively upon the quantum numbers of the exchanged particles. If only a single isovector particle, such as the \(\pi\) or \(\rho\), were exchanged then, neglecting the differences between the initial and final \(NN\) interactions, one would expect \(\sigma_{tot}(pn \rightarrow pn\omega) / \sigma_{tot}(pp \rightarrow \omega) = 5\). This would explain most of the 6.5 factor found in the \(\eta\) case [6]. Assuming that the ratio \(d\omega\) to \(pp\omega\) is as for \(\eta\) production, the parametrisation of the available \(pp \rightarrow pp\omega\) data [21] leads to the solid curve, which lies about a factor of three above our data. Another estimate is a little lower but similar in shape [23]. Both curves lie within the extremes of the predictions of the Jülich theory group [24], where the major uncertainty arises from the relative strengths of production and exchange current terms.
Taking our 90% C.L. upper limit on the cross section, augmented by the corresponding systematic uncertainty, would barely bring the data into agreement with the solid line of Fig. Even considering only these upper limits, the model predictions appear higher than the data. Any theoretical overestimation might be explained if there were significant isoscalar exchange, perhaps through the $\omega$ itself.

In summary, we have carried out the first measurement of the $pn \to d\omega$ reaction by detecting the spectator proton from a deuterium target in coincidence with a fast deuteron. Although the data are of very limited statistical significance, they suggest that the cross section lies below the published theoretical predictions.

In order to clarify the situation further, we are constructing second generation silicon telescopes that will increase the acceptance significantly. It would then be of interest to try to extend this study to the $\phi$ region so that one could investigate the OZI rule in the $I=0$ channel to see if the deviations are similar to those in the $I=1$ channel.

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