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Production of ω mesons in proton–proton collisions ☆

COSY-TOF Collaboration

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Abstract

The cross section for the production of ω mesons in proton–proton collisions has been measured in a previously unexplored region of incident energies. Cross sections of $\sigma = (7.5 \pm 1.9)$ µb and $\sigma = (30.8 \pm 3.4)$ µb (with 20% systematic uncertainties) were extracted at $\epsilon = 92$ MeV and 173 MeV excess energy above the ω threshold, respectively. The angular distribution of the ω at $\epsilon = 173$ MeV is strongly anisotropic, demonstrating the importance of partial waves beyond pure s-wave production at this energy.

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The production of mesons in nucleon–nucleon reactions is currently being investigated both experimentally and theoretically because of its implications for the understanding of the nuclear force. In the early nineties, the comparison of theoretical predictions to newly emerging experimental results on near-threshold meson production, in particular on $pp\pi^0$ [1] and, to a lesser extent, also other channels, revealed the rather poor understanding of the reaction mechanism of inelastic collisions between nucleons. Since then, a wealth of data has been accumulated for a number of mesons in the pseudoscalar sector, e.g., π, η, η', and K. Recently, investigations in the vector-meson sector (ρ, ω, ϕ) have come into focus. The exchange of these mesons dominates the nucleon–nucleon interaction at short distances.

The comparison of production cross sections of ω to that of ϕ mesons may shed light on a possible contribution of strange quark–antiquark pairs in the nucleon. While the ϕ contains almost only $s\bar{s}$, the ω wave function is practically decoupled from the strange sector, consisting of $u\bar{u} \oplus d\bar{d}$ only. The ϕ production should therefore be strongly suppressed, as predicted by the OZI rule [2]. A small contribution of 4×10^{-3} is expected because the mixing angle, $\Theta_V \approx 39°$ [3], deviates by 3.7° from that of a perfectly decoupled system in $SU(3)$, $\Theta_V = 35.3°$.

Recently, the DISTO collaboration found that the ϕ/ω production exceeds the OZI prediction by about one order of magnitude [4]. Their published data, however, were measured at one beam momentum setting of $Pc = 3.67$ GeV. Thus, the available kinetic energy in the overall CoM system (often referred to as excess energy, ϵ) is $\epsilon = 85$ MeV above the ϕ threshold but 320 MeV for the much lighter $pp\omega$ system. The extrapolation down to 85 MeV which covers more than one order of magnitude in cross section is far from straightforward. It is guided only by reference data measured below $\epsilon = 30$ MeV [5]. Measurements of ω production between $\epsilon = 30$ MeV and 300 MeV are crucial for a more detailed investigation of the excitation function and, thus, OZI violation in pp collisions.

While the ϕ angular distribution measured by the DISTO collaboration [4] is isotropic and therefore compatible with mere s-wave production, the ω distribution shows strong contributions from higher partial waves. If these persist at lower energies, as is the case in one of the possible scenarios in a recent theoretical calculation of Nakayama and coworkers [6], a quantitative comparison of ϕ and ω production may not be possible without a more detailed understanding of the underlying (and perhaps different) reaction mechanisms. Hence, experiments should aim at exclusive differential observables at lower excess energies.

In a first attempt to contribute to the issue of ω production in proton–proton collisions, data from an experiment at the time-of-flight spectrometer TOF located at an external beam line of the COoler SYnchrotron COSY at the Forschungszentrum Jülich were analyzed for a signal from ω production. The experimental setup was described in detail elsewhere [7]. The proton beam extracted from the synchrotron impinges on a thin liquid-hydrogen target [8]. In the present case, beam momenta of $Pc = 2.95$ GeV and 3.2 GeV are used. The reaction products leaving the target into the forward hemisphere generate, in a thin scintillator, a start signal for the successive time-of-flight measurement, then penetrate a silicon detector and two scintillating-fiber hodoscopes which permit an accurate track reconstruction needed for the detection of sequential hyperon decay [9]. After flight paths of more than 3 m in vacuum the particles are detected in a scintillator assembly with high angular coverage and good spatial and time resolution which consists of a barrel section [10] and a forward structure closing the cylindrical detector at small angles [11]. The detector covers polar angles from about 1° up to 70°.

The velocity vectors of charged particles thus measured were used in the analysis presented here. Events with four hits were selected for further inspection. A geometrical separation was applied in order to enrich events of the type $pp\pi^+\pi^-$, where the pions may originate from the decay of an intermediate resonance, e.g., $\eta \to \pi^+\pi^-\pi^0$ (BR 23%), $\rho^0 \to \pi^+\pi^-$ (BR 100%) or $\omega \to \pi^+\pi^-\pi^0$ (BR 89%), requiring two tracks with angles $\theta \leqslant 25°$ (assumed to be protons) and two more hits at larger angles (corresponding to the charged pions). This particle assignment is justified by kinematics which confines protons from $pp\omega$ reactions to the forward cone, while the much lighter pions can reach larger angles. The proton identification was further improved by a condition on velocities which rejects particles with velocities in excess of that of the beam. The proton four-momenta were used to calculate the missing mass of a hypothetical third particle, X. If X was a ρ^0, which exclusively decays into two charged pions, both pion directions can be combined to give the four-momentum of X. This also holds in case of nonresonant two-pion production where the four-momentum of X reconstructed from the missing-mass analysis of pp$X$ and that calculated with the $X \to \pi\pi$ hypothesis are required to agree within the detector resolution. In case of ω decay into three pions, a π^0 will be missing so that the detected pion pair will in most cases not be consistent with a two-body decay of X. This is demonstrated in Fig. 1, where spectra of the angle of acoplanarity between the pion directions with respect to the decaying meson are shown for the data (large frame) and for simulated $\rho^0 \to \pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$ events. The acoplanarity was defined as the deviation of the angle between the momenta of the pions taken in the rest frame of the decaying meson from 180° (i.e. back-to-back emission). The CoM momenta of the pions were calculated assuming a two-body decay of the primary meson X, as is the case for the ρ. In cases where this assumption holds, the deviation from a 180° opening angle remains small and peaks at 0°. The data clearly show a large two-pion production branch, which is rejected in the subsequent analysis as indicated by the dashed vertical line. Only events with acoplanarities larger than 25° were associated with three-body decays, $\pi^+\pi^-Y$. This criterion rejects more than 90% of the two-body events while reducing the amount of ω events by only 30%. Hence, it permits a clean identification of the ω production above a nonresonant background, mostly with multiplicities $n_\pi \geqslant 3$ as shown in the missing-mass plot of Fig. 2. The apparent width of the resonance is dominated by the detector resolution of $\sigma \approx 30$ MeV at this energy. The η meson also decays into three pions with 23% probability. The cross section for η production at these energies is about five times larger than that for ω production. Therefore, an appreciable amount of events in the figure may be due to η production. Because of the much lower mass of the η and the correspondingly higher available energy, the angular restrictions on the proton directions and velocities reduce the acceptance for η events to 1.9% compared with 6.4% for the ω and less than 0.5% for the ρ contribution to the spectrum in Fig. 2. Since the available energy is large, the protons which are detected in case of η production will have large velocities. Therefore, the missing-mass resolution for η mesons is much worse than for the heavier and kine-

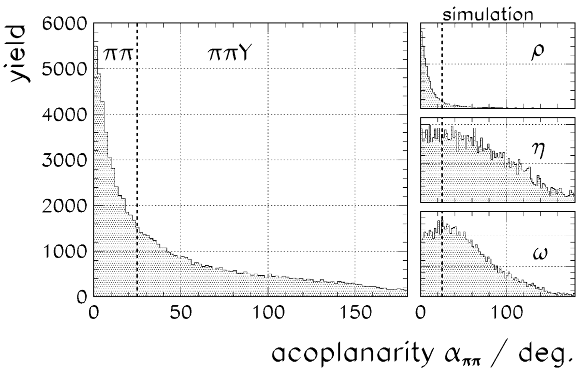

Fig. 1. Distribution of acoplanarity angles derived using the reconstructed momentum of the hypothetical meson X and the directions of its decay pions. The large frame shows the experimental spectrum which is used to separate two-pion events (labeled $\pi\pi$) to the left of the dashed line from those where an additional particle Y was involved. The small spectra to the right show the simulated angular distributions for the decays $\rho^0 \to \pi^+\pi^-$ and the three-body decays $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$.

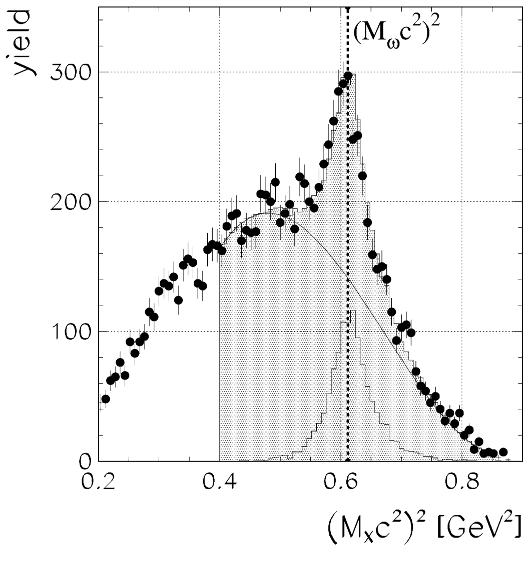

Fig. 2. Spectrum of the squared missing mass as reconstructed from two detected protons after enhancing cuts on the pions. The ω peak at ≈ 0.6 GeV^2 is clearly visible. The hatched peak at $(Mc^2)^2 = 0.6$ GeV^2 shows the simulated response function of the detector. It nicely agrees in shape with the ω signal above background, as demonstrated by the shaded area which is a sum of the parameterized background as indicated and the Monte Carlo ω signal (hatched peak).

matically constrained ω, so that an η signal is not observed in Fig. 2. The emission direction of X was restricted to forward emission, $\theta_X^* \leqslant 90°$. This event pattern is also favored by the detector acceptance. It yields protons sufficiently low in energy to allow calculation of the missing mass with the quoted precision, while the backward emission of X boosts the protons to higher velocities so that the missing-mass resolution degrades with increasing angle of X. The experimental mass spectrum (data points with statistical errors) exhibits a peak at the ω mass which is well reproduced in shape and position by the detector Monte Carlo (hatched peak for the ω) when added to a parameterized background, as shown by the shaded spectrum. The small remaining shift in position is due to calibration uncertainties in the time-of-flight determination. The missing-mass peak of Fig. 2 can be integrated to yield the total number of ω mesons produced. Different background shapes were applied in fits to the distribution. They produce cross sections for the ω which are consistent to within ±10%. The background used in producing Fig. 2 is taken to be a third order polynomial which has been fitted to the distribution above and below the peak in the indicated region. While, in principle, a background estimation using simulations which incorporate nonresonant as well as resonant multipion production appears desirable, the lack of differential cross-section data prevents doing so.

The normalization of the data requires a luminosity calibration which is easily accomplished in our experiment due to the simultaneous measurement of elastically scattered protons over a wide angular range. These data can then be compared to the results of other experiments which measured the elastic scattering to a high level of precision (see, e.g., [12]) and/or phase-shift analyzes [13]. The overall normalization uncertainty from this procedure is estimated to be about 5%. After correction for the acceptance of the setup using Monte Carlo simulations, total cross sections can be deduced. They are shown in Fig. 3 together with results from the literature [14,15] and theoretical calculations [16–18]. The acceptance calculations include detector resolution as well as all the conditions applied to the data. The overall acceptance for ω events at 173 MeV is 6.4% with only a small modulation with angle (7.1% at 92 MeV). A systematical uncertainty which is larger than the statistical errors comes

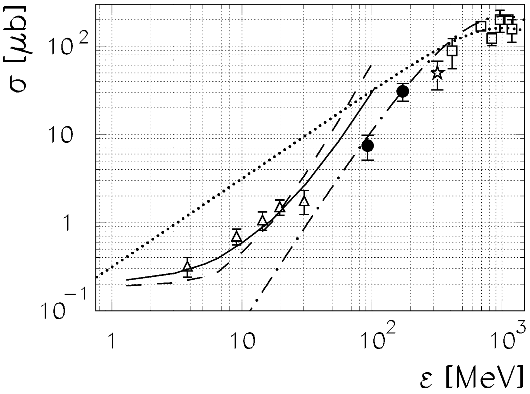

Fig. 3. Excitation function of pp → ppω. The lines are theoretical calculations by Cassing ([16], dotted line), Sibirtsev ([17], dash-dotted line) and Nakayama and coworkers ([18], solid and dashed lines) which are discussed in the text. The filled circles are the present data, while the open triangles are from the SPES3/Saturne experiment [5], the star is from DISTO/Saturne [14]. The errors shown include systematic as well as statistical errors which were added quadratically. The open squares represent data adopted from a compilation of cross sections [15].

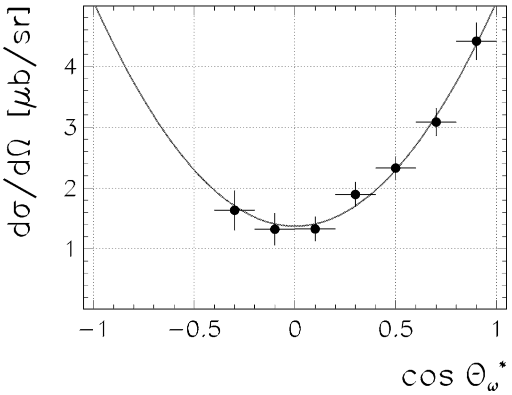

Fig. 4. Angular distribution of the ω in the overall center-of-momentum frame. Only the forward part, $\cos\theta_\omega^* \geqslant -0.3$, is displayed since the analysis is restricted to this region. The full line is a fit with the lowest two even Legendre polynomials.

about when an angular distribution of the ω mesons is taken into account in the acceptance calculations. To this end, the isotropic three-body phase space was modified in an iterative procedure to fit the observed anisotropy (cf. Fig. 4) at 173 MeV. This changes the deduced cross section by almost 20%. Since the current analysis does not permit the extraction of angular distributions at the lower energy, anisotropies cannot be excluded in this case. It is however reasonable to assume that these will not exceed those determined at twice the excess energy, so that the same anisotropy was used for both energies to estimate the resulting change in cross section. This prescription yields a decrease in cross section by 13% (about half of the statistical error) at the lower energy and an increase by 19% at the higher energy (almost twice the statistical error). This is caused by the different ranges of momenta accessible to the ω and protons at the two energies. In particular, the kinematic focusing of the pions from ω decay is very different in both cases. This changes the acceptance of the detector differently at the two energies. The displayed cross sections are $\sigma = (7.5 \pm 1.9)$ µb at $\epsilon = 92$ MeV and $\sigma = (30.8 \pm 3.4)$ µb at 173 MeV, respectively, where in the latter the angular distribution of the ejectiles was taken into account in the acceptance correction. The corrections to the data due to background subtraction, acceptance calculations employing various conditions such as, e.g., using phase space distributions for the ω decay pattern instead of the vector-meson decay, do not alter the deduced cross sections by more than 20% as was also obtained from the anisotropy considerations. Thus, we conclude that the absolute numbers for the total cross sections given here are subject to systematic uncertainties not larger than 20% which are included in the error bars of Fig. 3.

Neither of the theoretical excitation functions based on parameterizations of one-pion exchange model calculations (dotted [16] and dash-dotted [17] lines in Fig. 3) is able to describe the measured data at low energy. The parameterization given by Sibirtsev [17] comes closer to the data than the one by Cassing [16] but fails below 90 MeV where final-state interactions may start to contribute.

There is a general agreement among various theorists [18–22] that ω and ϕ production, when viewed in a meson-exchange picture, can be ascribed to two dominant contributions which are called “nucleonic” when the meson is emitted by one of the nucleons (NNυ vertex, υ denotes either vector meson, ϕ or ω) in contrast to the “mesonic” current where the emitted vector meson originates from the exchanged meson, e.g., from a $\rho\pi\upsilon$ vertex. The solid and dashed lines in Fig. 3 show two calculations by Nakayama et al. [18] within such a model. Different sets of parameters for both the nucleonic and mesonic currents were used. The parameters for ϕ and ω, in particular the coupling constants, were related by $SU(3)$ considerations. The form factor for the mesonic current was fixed to the ϕ angular distribution at 85 MeV which is flat to within the—rather large—experimental errors [4]. The vector coupling constants for the $\rho\pi\upsilon$ vertices were taken from $\phi \to \rho\pi$ and $\omega \to \gamma\pi$ decay, respectively, while the tensor-to-vector ratio was varied within reasonable limits, $\kappa_\upsilon = \pm 0.5$. Left with the cutoff parameter for the nuclear contribution form factor, the total ppω cross sections [5] were fitted. Finally, the NNϕ coupling constant was adjusted to fit the nuclear contribution to the ϕ angular distribution. While both calculations fail to reproduce our data, the solution with negative tensor coupling, $\kappa_\upsilon = -0.5$ (solid line), gives a better agreement in overall shape. It uses a rather small cutoff parameter, $\Lambda_{\mathrm{N}} = 1170$ MeV, and results in a coupling constant of $g_{\mathrm{NN}\phi} = -0.45$. Because of the decreasing nuclear contribution with decreasing Λ_{N} and the destructive interference of vector and tensor currents, this solution results in an angular distribution which is completely dominated by the mesonic current. Hence, a flat distribution is expected, as is indeed observed in the case of ϕ production. However, the anisotropic ppω angular distribution for an excess energy of 173 MeV which is shown in Fig. 4 suggests that this parameter set cannot describe the ω production. The figure does not include the most backward-emitted mesons because of the aforementioned bias toward low-momentum protons needed in the analysis. Since the entrance channel is symmetric the distribution has to be symmetric about $\cos\theta^*_\omega = 0$ as indicated by the two data points below $\cos\theta^*_\omega = 0$. The angular distribution of protons was indeed found to be symmetric. The acceptance corrections used to determine the differential cross sections were deduced separately for each interval in $\cos\theta^*_\omega$. A decrease in acceptance from 12% to 7% is observed when going from $\cos\theta^*_\omega = 0$ to $\cos\theta^*_\omega = 1$, while the ω yield increases by a factor of two over the same range. Hence, the observed anisotropy is somewhat amplified by the acceptance correction, however the effect is already contained in the uncorrected data. The strong anisotropy which was also observed in [4] for 320 MeV excess energy suggests that higher partial waves may be present even at lower energy where, according to [6], this may be viewed as direct proof of the dominance of nucleonic currents. A fit with the lowest two even Legendre polynomials yields coefficients of $a_2/a_0 = 2.5(\pm 0.3)/2.6(\pm 0.1)$ compared to $3.1(\pm 0.2)/4.0(\pm 0.1)$ at 320 MeV [14] where, in addition, a P_4 contribution was needed which is not required here.

Using our ω cross-section value at 92 MeV together with the ϕ cross section [23] at 85 MeV yields a production ratio $\sigma_\phi/\sigma_\omega$ of about $(3 \pm 1)\%$. This is, although smaller than the DISTO estimate without the current cross section, about a factor of 7 larger than the OZI prediction. The uncertainty is dominated by the experimental error on the ϕ cross section. The current result also exceeds the prediction of about 1% for the ratio at this energy in [19] for small NNϕ coupling. More detailed studies are however needed before final conclusions will emerge.

With envisaged improvements in experimental techniques, especially in accepted luminosity, also ϕ production may come into reach at COSY. Further experimental investigations will then help to shed light on the question of the strange content of the nucleon addressed in vector-meson production.

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