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Near-threshold production of ω mesons in the $pd \rightarrow {}^3\mathrm{He}\,\omega$ reaction

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Backward $\omega(782)$-meson production in the $pd \rightarrow {}^3\mathrm{He}\,\omega$ reaction has been measured from threshold up to an ω center-of-mass momentum of 625 MeV/c. The averaged squared amplitude rises rapidly from threshold to a maximum value of about 70 nb/sr at 180 MeV/c, decreasing thereafter. This striking behavior, which is very similar to that already observed for $\pi^- p \rightarrow n\omega$, may be caused by a final-state interaction between the pions from the ω decay and the recoil nucleus.

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The production of $\omega(782)$ mesons in the $\pi^- p \rightarrow n\omega$ reaction was extensively studied from threshold up to an ω center-of-mass (CM) momentum $p^*_\omega = 200$ MeV/c by a Nimrod group during the 1970's [1,2]. The measured differential cross sections were isotropic and consistent with S-wave production but, in contrast to the threshold enhancement seen in η production [1], the ω amplitude was sharply suppressed at small p^*_ω. No similar effects were observed for η' or ϕ production [1]. They gave two alternative interpretations of the ω suppression as being due to either (1) a particular combination of S- and P-wave ωN resonances, or (2) a final-state interaction between the decay products of the ω meson and the recoil neutron. It is interesting to see whether this threshold effect persists in more complex reactions and in particular in $pd \rightarrow {}^3\mathrm{He}\,\omega$, which had been systematically studied only at much higher energies [3]. The sole experiment carried out near threshold was performed at the Saturne II synchrotron of the Laboratoire National Saturne (LNS) using the SPES 4 double-focusing high-resolution magnetic spectrometer [4], but this led to only preliminary results [5].

The present experiment makes use of the same apparatus, but was designed for fine scanning of the threshold excitation function of the $pd \rightarrow {}^3\mathrm{He}X$ reaction from the ω to the ϕ meson [6,7]. The 1.3–1.9 GeV proton beam, of average intensity $2\times10^{11}\ \mathrm{s}^{-1}$, was focused on a 38 mm thick LD_2 (616 mg/cm^2) target. Between the target and collimator, which limited the solid angle to 0.1 msr, a dipole was placed to separate ^{3}He's from beam protons at 0°. As the separation was only a few degrees, the proton beam was driven onto the lead of the collimator and some protons scattered into the spectrometer. The momentum acceptance of SPES 4 was $\Delta p/p = \pm 3\%$.

Two scintillator hodoscopes, placed in the intermediate (I) and final (F) focal planes, served for both effective particle discrimination, by time-of-flight (TOF) measurements, and as the main trigger. The long TOF path of 16.2 m and good time resolution of these counters [better than 800 ps full width at half maximum (FWHM)], allowed perfect off-line discrimination, but also gave a very efficient on-line cut using an ultrafast coincidence unit [8]. Further optimization of this trigger was obtained by lowering the high voltages of the photomultipliers of both hodoscopes such that most of the residual protons from the beam could not pass the threshold. This still kept the 100% efficiency for ^{3}He's.

The same technique also was used for two sets of multiwire drift chambers [9] placed in front of the final hodoscope. By lowering their high voltages, the enormous flux of protons was only partially seen by the chambers, allowing measurements at high incident intensities. The chamber efficiency for ^{3}He's was not affected and more than 94% of the particle tracks were reconstructed. Using the known inverse transport matrix of SPES 4 [10], the chamber information was used to test whether or not the detected particles came from the deuterium target.

The incident flux was continuously monitored by two scintillator telescopes, viewing a 50 μm Mylar foil far from the target. These telescopes have a relative stability of better than 1%. However, after beam energy changes or machine problems, larger fluctuations occasionally happened. In such cases normalization was made possible by a secondary electron monitor with a long term stability of 3%. Another telescope controlled the deuterium target during the whole experiment. Absolute calibration was provided to $\pm 5\%$ by the ${}^{12}\mathrm{C}(p,pn){}^{11}\mathrm{C}$ activation method [11]. Target-empty measurements showed that the contribution of ^{3}He's from the titanium (31 mg/cm^2) and aluminum (6.5 mg/cm^2) windows was approximately constant (always less than 20%) and led to no structure in the focal-plane momentum spectrum.

For measurements away from threshold, the spectrometer was tuned to be sensitive to the central mass value of an ω produced in the backward direction $\theta^*_\omega = 180°$ in the two-body $pd \rightarrow {}^3\mathrm{He}\,\omega$ reaction. These measurements were performed at 20 different beam energies up to $T_p = 1900$ MeV,

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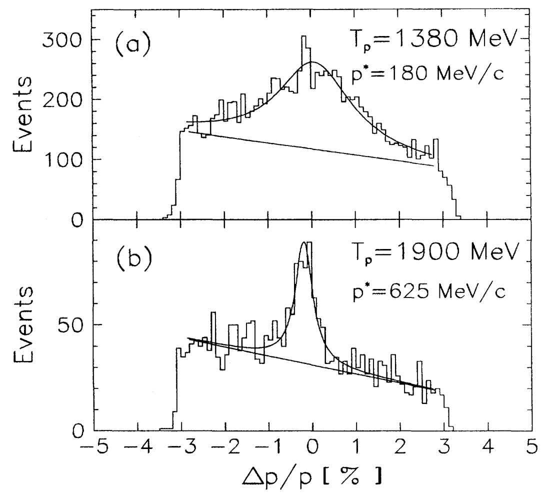

FIG. 1. Momentum spectra for the $pd \rightarrow {}^3\mathrm{He}\,\omega$ reaction at (a) 1380 MeV and (b) 1900 MeV. The apparent peak width depends strongly on kinematical features. The curves are Breit-Wigner fits of an ω signal over a linear multipion continuum.

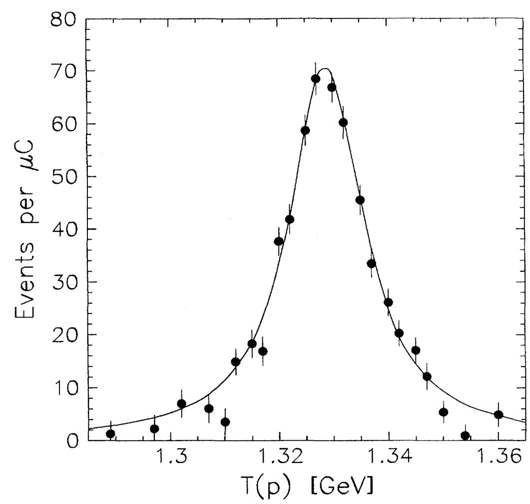

FIG. 2. Near-threshold counting rates normalized to the incident beam current. The curve is the resultant angular and momentum acceptance after folding in the relative yield for ω production.

starting at the nominal ω threshold of $T_p = 1325.6$ MeV. Typical F-focal plane momentum spectra of the ^{3}He are shown in Fig. 1 for $T_p = 1380$ and 1900 MeV, corresponding to $\omega\,{}^3$He CM momenta $p_\omega^* \approx 180$ and 625 MeV/c. Even far above threshold the width due to ω production is nonnegligible and the apparent width change in Fig. 1 is a kinematic effect. The fits correspond to a Breit-Wigner peak from the Monte Carlo simulations with standard width (8.43±0.10 MeV/c^2) [12] plus a linear continuum contribution. The decrease in the continuum towards higher momenta is also observed in the threshold excitation function measurements [6,7].

Kinematic conditions vary rapidly in our energy domain and this affects greatly the spectrometer acceptance. Near threshold the total missing mass acceptance is very small (FWHM ≈1 MeV/c^2) compared to the ω width. At $T_p = 1500$ MeV (180 MeV above threshold) the acceptance covers more than 90% of the ω peak. While far above threshold the transformation of laboratory to CMS cross sections could be done with an averaged Jacobian, at low p_ω^* a Monte Carlo technique was necessary to describe the acceptance variation and to correct the counting rates for nonobserved quantities.

Measurements very close to threshold ($p_\omega^* \approx 20$ MeV/c) were performed by the threshold-crossing method [2] as part of the threshold excitation function measurements in the $pd \rightarrow {}^3\mathrm{He}\,X$ reaction [6,7]. The spectrometer was tuned to be sensitive to the maximum possible missing mass of the system X, i.e., $p_{\mathrm{He}}^* = p_X^* = 0$. The maximum missing mass is given by $m_X = W - m_{\mathrm{He}}$, where W is the total energy in the CMS. Under such conditions the laboratory momentum of the detected ^{3}He is $p_{\mathrm{He}}^{\mathrm{thres}} = p^{\mathrm{inc}} m_{\mathrm{He}}/(m_{\mathrm{He}} + m_X)$, where p^{inc} is the incident proton beam momentum. ^{3}He momenta higher or lower than the central value correspond to nonzero p^* and hence to smaller masses of the unobserved system X. The spectrometer accepted $0 \leq p_{\mathrm{He}}^* \leq 45$ MeV/c and this stayed essentially constant for different beam energies. We scanned through the whole ω peak in mass steps of 1 to 1.5 MeV/c^2, corresponding to changes in beam energy of 2 to 3 MeV.

Our Monte Carlo code assumes an isotropic CM distribution, taking into account beam energy spread and aperture effects as well as energy loss and straggling in the target and I hodoscope [6]. For the near-threshold data this leads to a mass resolution of better than 100 keV/c^2 (FWHM). In the worst case of the highest beam energy of $T_p = 1900$ MeV [see Fig. 1(b)], kinematic effects degrade the mass resolution to about 2 MeV/c^2. The results of the simulation are given in Fig. 2. The curve represents the folding of the angular and momentum acceptance with the integrated yield over the Breit-Wigner resonance [13]. The resulting yield prediction, compared with our data in Fig. 2, is very like the input Breit-Wigner peak, though broadened mainly by the energy losses in the target. Note that the rise on the low-energy side comes from the increase of the integral over the the Breit-Wigner resonance while the decrease on the high-energy side is the result of the spectrometer tuning no longer favoring the ω mass but rather the maximum possible missing mass (threshold crossing method). The Monte Carlo gives directly the dependence of the Jacobian $J = d\Omega^{\mathrm{lab}}/d\Omega^*$ on the beam energy. Note that at the nominal threshold of 1325.6 MeV only half of the total resonance can be excited but ω's are produced below this energy due to their finite width. A χ^2 fit to the data with a Breit-Wigner formula, allowing width, center, and relative normalization of the curve to vary freely, leads to a differential cross section $d\sigma/d\Omega^* = (0.24 \pm 0.01)$ nb/sr. Just as in the Nimrod experiments [1], this result is to be interpreted as the cross section for the full ω peak at a *fixed* value of $p_\omega^* = (21 \pm 12)$ MeV/c, different parts of the Breit-Wigner being measured at slightly different beam energies. The fit was checked by introducing the same parameters into the simulation and this gave a curve indistinguishable from that of Fig. 2.

The total near-threshold data set shown in Fig. 2 corresponds to about 19 500 events and the error bars shown are only statistical. As the ω signal is spread over the whole focal plane of the spectrometer, the data were corrected for

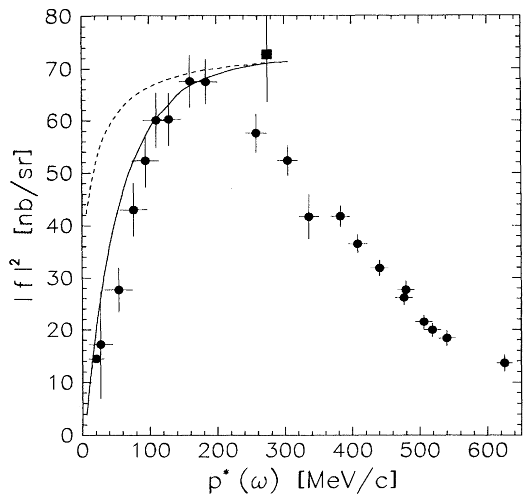

FIG. 3. Average squared amplitudes $|f_\omega|^2$ for the $pd \to {}^3\text{He}\,\omega$ reaction as a function of p^*_ω for $\theta^*_\omega = 180°$. The lowest point represents the data from Fig. 1. The square is from Ref. [16]. The solid line shows a simulation for the ω decay into three pions while the broken one shows the $\pi^0\gamma$ case.

other $pd \to {}^3\text{He}\,X$ contributions by interpolating the continuum measured away from the ω peak [6]. Systematic errors associated with this subtraction are less than 4.5%.

The central mass derived from the Monte Carlo simulation is $(782.7 \pm 0.1 \pm 1.5)$ MeV/c^2, where the 1.5 MeV/c^2 error bar arises from the uncertainty in the absolute beam energy determination [14]. This result is in good agreement with the standard value of (781.94 ± 0.14) MeV/c^2 [12]. Our value of the ω width, (8.2 ± 0.3) MeV/c^2, is the most precise measurement of this quantity performed in a hadronic missing-mass experiment and demonstrates again the precision of the SPES 4 facility. It is in significantly better agreement with the Particle Data Group compilation of (8.43 ± 0.10) MeV/c^2 [12] than that of Ref. [1].

We define the averaged squared amplitude by factoring out the phase space,

$$|f_\omega|^2 = \frac{p^*_p}{p^*_\omega}\left(\frac{d\sigma}{d\Omega^*}\right)_{180°}. \qquad (1)$$

Our values of $|f_\omega|^2$ are shown in Fig. 3 as a function of p^*_ω. The lowest point corresponds to the threshold data of Fig. 2. Horizontal error bars come from the FWHM of the SPES 4 acceptance and the energy loss in the target, whereas vertical ones reflect the spread of values of p^*_ω as well as the uncertainty of the fits determining the counting rates and the background subtraction shown in Fig. 1. The most striking feature is the suppression of $|f_\omega|^2$ at low p^*_ω. This does *not* arise from phase-space cutting into the resonance width, which has been taken into account in the data analysis. A very similar effect was observed in $\pi^- p \to n\omega$, [1,2] where there was strong evidence for S-wave dominance from the isotropy of the angular distribution up to $p^*_\omega \approx 200$ MeV/c. For S-wave production $|f_\omega|^2$ should approach a nonzero constant at threshold and conventional final-state interactions, which describe η production well in $\pi^- p \to n\eta$ and $pd \to {}^3\text{He}\,\eta$ [15], always lead to threshold enhancements rather than suppressions. Though we did not measure angular distributions, new SPES 3 data [16] give indication of some higher partial waves in $pd \to {}^3\text{He}\,\omega$ reaction at $p^*_\omega \approx 270$ MeV/c, but this is well above the threshold dip. Their result for backward production is also shown in Fig. 3.

The suppression was first interpreted in Ref. [1] as being due to the ω decaying before leaving the recoil neutron; at $p^*_\omega = 20$ MeV/c the typical decay length is only 1 fm. Pions from such a decay have a high probability of scattering from the neutron, changing its momentum and removing the signal of an ω peak from the neutron TOF spectrum. In fact the average momentum of the decay pions in the ω rest frame is 220 MeV/c, which is close to the maximum in the πN total cross section. The effect disappears at high p^*_ω because the ω then lives long enough to escape the nuclear environment.

This hypothesis was abandoned for two reasons [2]:

(1) The observed ω width seemed to be independent of p^*_ω whereas, if rescattering broadened it, then the ω should be wider at low p^*_ω.

(2) The later experiments separated the two main decay channels, viz. $\omega \to \pi^- \pi^+ \pi^0$ (88.8%) and $\omega \to \pi^0\gamma$ (8.5%) and found that the relative branching ratio seemed to be independent of p^*_ω. One would of course expect the pion rescattering effect to be more important in the three-pion case than for the radiative decay.

Binnie *et al.* instead fit their data [2] by taking two N^* resonances, viz. $S_{11}(1650)$ and $P_{11}(1710)$ which, with appropriate couplings, can conspire to give an isotropic cross section but with a strong p^*_ω behavior coming from the P-wave nature of the $N^*(1710)$. However, apart from the complexity of the solution, photoproduction data show only a small coupling of this resonance to γ-N and, by vector meson dominance, this is likely to be the case also for ωN. The conspiracy is also unlikely to remain intact going from the πN to the pd systems.

On the other hand, there must be an effect coming from the scattering of one or more decay pions from the recoil nucleus. Any such scattering would almost certainly knock the detected particle completely out of the kinematics of the ω peak into the multipion continuum rather than broadening the peak, which was not observed in either of the two reactions. We have made a rough estimate of this effect in a naive *classical* Monte Carlo model, where the ω decay vertex was chosen randomly according to the decay length. An interaction was assumed if the trajectory of one of the pions fell within the solid angle defined by the ^{3}He cross section. The solid line shown in Fig. 3 is the result of the simulation for the $\pi^- \pi^+ \pi^0$ decay and the broken one that for the minor $\pi^0\gamma$ branch, assuming the basic production amplitude to be independent of p^*_ω. A very similar behavior is found for $\pi^- p \to n\omega$ [13] and the only free parameters are the absolute normalizations in the two cases. Although, as expected, the $\pi^0\gamma$ decay is less suppressed near threshold, the magnitude of the effect and its range in p^*_ω are well described for the dominant 3-pion mode. However, it casts no light on why Binnie *et al.* found the $\pi^0\gamma$ decay to be equally suppressed. It is clear that a full quantum mechanical treatment of the problem is required in order to draw more quantitative conclusions.

In summary, our measurements show that, as for pion-induced production, the near-threshold cross section for $pd \rightarrow {}^3\mathrm{He}\,\omega$ seems suppressed for $p_\omega^* < 200$ MeV/c compared to a simple S-wave assumption. Although without measurements of the angular distributions we cannot exclude strong P-wave production at low energies, the most likely explanation is a final-state interaction where a pion from the ω decay scatters from the recoil nucleus and our simplistic classical calculation gives a plausible description of this feature. A value for the ω width was found which is in good agreement with the world average [12].

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[1] D.M. Binnie *et al.*, Phys. Rev. D **8**, 2789 (1973).
[2] J. Keyne, D.M. Binnie, J. Carr, N.C. Debenham, A. Duane, D.A. Garbutt, W.G. Jones, I. Siotis, and J.G. McEwen, Phys. Rev. D **14**, 28 (1976); H. Karami, J. Carr, N.C. Debenham, D.A. Garbutt, W.G. Jones, D.M. Binnie, J. Keyne, P. Moissidis, H.N. Sarma, and I. Siotis, Nucl. Phys. **B154**, 503 (1979).
[3] H. Brody, E. Groves, R. Van Berg, W.D. Wales, B. Maglich, J. Norem, J. Oostens, M. Silverman, and G.B. Cvijanovich, Phys. Rev. D **9**, 1917 (1974).
[4] E. Grorud, J.L. Laclare, A. Ropert, A. Tkatchenko, J. Banaigs, and M. Boivin, Nucl. Instrum. Methods **188**, 549 (1981).
[5] F. Plouin, in *Production and Decay of Light Mesons*, edited by P. Fleury (World Scientific, Singapore, 1988), p. 114.
[6] R. Wurzinger, Ph.D. thesis, University of Bonn, ISKP-Report No. 3/1992.
[7] R. Siebert, in *Proceedings of the Workshop on Meson Production, Interaction and Decay*, Cracow, 1991, edited by A. Magiera (World Scientific, Singapore, 1991); M.-A. Dural *et al.*, Few-Body Systems, Suppl. 7, p. 247 (1994); see also [5].
[8] IPN Orsay Technical Annual Report, 1989, p. 10; see also C. Lippert, Ph.D. thesis, University of Bonn, 1990; and R. Siebert *et al.*, Nucl. Phys. **A567**, 819 (1994).
[9] M. Bedjidan *et al.*, Nucl. Instum. Methods Phys. Res. Sect. A **257**, 132 (1987).
[10] M. Boivin and J.M. Durand, Internal LNS report, 1984.
[11] J. Banaigs, J. Berger, J. Duflo, L. Goldzahl, O. Harff, M. Cottereau, F. Lefebvres, H. Quéchon, and P. Tardy-Joubert, Nucl. Instrum. Methods **95**, 307 (1971).
[12] Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994).
[13] R. Wurzinger, in Proceedings of 14th International Conference on Few Body Problems in Physics, Williamsburg, 1994, edited by F. Gross (AIP, New York, in press).
[14] F. Plouin *et al.*, Phys. Lett. B **276**, 526 (1992).
[15] C. Wilkin, Phys. Rev. C **47**, R938 (1993).
[16] T. Kirchner, Ph.D. thesis, IPN Orsay, 1993.