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Polarisation of the ω meson in the $pd \to {}^3\mathrm{He}\omega$ reaction at 1360 and 1450 MeV

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ABSTRACT

The tensor polarisation of ω mesons produced in the $pd \to {}^3\mathrm{He}\omega$ reaction has been studied at two energies near threshold. The ${}^3\mathrm{He}$ nuclei were detected in coincidence with the $\pi^0\pi^+\pi^-$ or $\pi^0\gamma$ decay products of the ω. In contrast to the case of ϕ-meson production, the ω mesons are found to be unpolarised. This brings into question the applicability of the Okubo–Zweig–Iizuka rule when comparing the production of vector mesons in low energy hadronic reactions.

The production of the light isoscalar vector mesons ϕ and ω in various nuclear reactions involving non-strange particles are often compared within the framework of the Okubo–Zweig–Iizuka rule [1]. This rule suggests that processes with broken quark lines are suppressed, and therefore the cross section ratio between ϕ and ω production is mainly due to small deviations from ideal mixing of these mesons at the quark level. The ratio of the squares of the production amplitudes for the two mesons, for any hadronic reaction measured under similar kinematic conditions, should be of the order of $R_{\phi/\omega} \approx R_{\mathrm{OZI}} = 4.2 \times 10^{-3}$ [2]. The validity of this estimate has been tested for the $pd \to {}^3\mathrm{He}\omega/\phi$ reaction near threshold, where it was found that $R_{\phi/\omega} \approx 20 \times R_{\mathrm{OZI}}$ [3–5]. This deviation is over a factor of two greater than that found, for example, in

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the case of production in nucleon–nucleon collisions near threshold [6,7]. It is thus unclear to what extent the OZI approach is applicable for this reaction, and further experimental input would be valuable.

In the MOMO study of the $pd \to {}^3\mathrm{He}\phi$ reaction [5], the K^+ and K^- coming from the decay of the ϕ were measured in coincidence with the ^{3}He ejectile. Now the angular distribution of the K^+K^- relative momentum in the rest frame of the ϕ-meson is sensitive to the tensor polarisation (spin alignment) of the spin-one meson. The surprising result from the MOMO experiment is that near threshold the ϕ are produced almost purely in the magnetic substate with $m = 0$ along the beam direction [5]. In the light of the OZI consideration in comparing the cross sections of the ω and ϕ production it should also be interesting to compare the polarisation of these mesons produced in the $pd \to {}^3\mathrm{He}\omega/\phi$ reactions, since any difference in the ω/ϕ polarisation is not expected to depend on the details of the quark mixing but rather on the reaction mechanism.

The only two significant decay channels of the ω meson are $\omega \to \pi^0\pi^+\pi^-$ and $\omega \to \pi^0\gamma$, with branching ratios of 89.1% and 8.7%, respectively [8]. The angular distributions of both decays reflect the spin alignment of the ω. By measuring both these channels, we obtained two different measurements for the ω polarisation in the $pd \to {}^3\mathrm{He}\omega$ reaction.

The measurements of the ω polarisation were carried out at The Svedberg Laboratory in Uppsala, Sweden, using the WASA detector [9,10], which was an integral part of the CELSIUS storage ring. The experiments were done at $T_p = 1360$ and 1450 MeV, corresponding to excess energies of 17 and 63 MeV with respect to the nominal ${}^3\mathrm{He}\omega$ threshold. The circulating proton beam was incident on deuterium pellet targets [11,12]. The ^{3}He ejectiles were measured in the WASA forward detector (FD), which covered laboratory polar angles from 3° to 18°. This corresponds to 95% of the ^{3}He phase space for ω production at 1450 MeV and 78% at 1360 MeV. The majority of the lost events are those where the ^{3}He are emitted at small laboratory angles such that they escape detection down the beam pipe. The corresponding angular acceptance of the ω mesons covers, in the CM system, the intervals 22°–158° at 1450 MeV and 46°–134° at 1360 MeV.

The forward detector consists of sector-like scintillation detectors forming a window counter (FWC) for triggering, a hodoscope (FTH) for triggering and off-line particle identification, a range hodoscope (FRH) for energy measurements, particle identification and triggering, and a veto hodoscope (FVH) for triggering. A proportional chamber (FPC) for precise angular information is also part of the forward detector. Mesons and their decay products are mainly measured in the central detector (CD) that consists of the Plastic Scintillating Barrel (PSB), the Mini Drift Chamber (MDC), the Super Conducting Solenoid (SCS), and the CsI equipped Scintillating Electromagnetic Calorimeter (SEC). The SEC, which measures the angles and energies of photons arising from meson decay, covers polar angles from 20° to 169°. A schematic overview of the setup is shown in Fig. 1.

The hardware ^{3}He trigger selected events where there was a hit with a high energy deposit in the FWC as well as a hit in either the FTH (March 2005 run) or the FRH (May 2005 run) in the same ϕ angle sector.

The ^{3}He was identified in the FD using the $\Delta E - E$ method, as described in Ref. [13]. Here the light output from the detector layer where the particle stopped was compared with that from the preceding layers. The χ^2 of a particular particle hypothesis was then calculated by comparing the measured energy deposits in all detector layers traversed to those expected for that particle. Particle hypotheses giving a χ^2 larger than a maximum value, chosen to reduce background without losing good events, were rejected [14].

The main focus of the present work is on the $\omega \to \pi^0\pi^+\pi^-$ decay channel, where the large branching ratio (89.1%) gives the highest statistics. To select this channel we require one ^{3}He with a well defined energy and angle in the FD and at least two photons in the SEC. In addition, one photon pair must have an invariant mass close to that of the π^0. The missing mass of the ${}^3\mathrm{He}\pi^0$ system must be larger than 250 MeV/c^2, i.e., twice the pion mass folded with the experimental resolution, in order to select the events with two additional pions. The two charged pions are included by requiring two or more hits in the PSB. Finally, we require at least one track in the MDC coming from the overlap region between the pellet target and the proton beam. The missing mass of the ^{3}He is shown in Fig. 2(a) for all events fulfilling the above criteria.

The selection requirements lead to an overall acceptance of 14% at both beam energies. In addition to the losses at small angles in the beam pipe, there are losses from the ^{3}He that undergo nuclear interactions before depositing all their energy. Moreover photons from π^0 decay can escape detection in the CD and, finally, there is the limited MDC efficiency ($\approx 50\%$). About 10% (30%) of the events at 1450 (1360) MeV are produced outside the pellet target (mainly in beam-rest gas interactions) and are therefore rejected.

For an ω meson decaying into $\pi^0\pi^+\pi^-$, the spin direction can be specified with respect to an axis directed along the normal to the decay plane. This direction is given by the vector product of the momenta of the π^0 and one of the charged pions in the rest frame of the ω meson. For this purpose, the π^0 was reconstructed from the decay photons, and the charged pion from the precise angular determination in the MDC combined with the information from the ^{3}He and the π^0.

The polarisation can be measured by studying the dependence of the cross section on the angle β between the normal and some quantisation axis in the Gottfried–Jackson frame [15], i.e., the rest frame of the ω. For the Jackson angle the quantisation axis is taken to be along the direction of the proton beam.

We are interested in the elements of the spin-density matrix $\rho_{mm'}$ that represent the tensor polarisation (alignment) of the ω. With an unpolarised beam and target, there is one independent term $\rho_{11} = \rho_{1-1} = \frac{1}{2}(1 - \rho_{00})$ that can be measured. The dependence of the differential cross section on β is of the form:

$$\frac{\mathrm{d}\sigma(\omega \to \pi^0\pi^+\pi^-)}{\mathrm{d}\cos\beta} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\beta. \tag{1}$$

If the ω mesons are unpolarised, one has that $\rho_{00} = \rho_{11} = \rho_{1-1} = \frac{1}{3}$ and thus an isotropic angular distribution, while the maximum polarisation occurs when $\rho_{00} = 1$ and thus the distribution has a pure $\cos^2$ dependence.

In order to obtain the differential cross section as a function of $\cos^2\beta$, all events fulfilling the selection criteria were divided into eight regions of $|\cos\beta|$. In view of the limited statistics, no account was here taken of the ω direction in the CM system. Any possible dependence on the ω direction will be discussed later. In each region of $|\cos\beta|$ the missing mass of the ^{3}He (MM(^{3}He)) was plotted. The ω candidates show up in a peak near the nominal mass at 782.6 MeV/c^2, as clearly seen in the event distribution shown in Fig. 2(a). The background under the ω peak was estimated in two ways, either by taking a phase-space Monte Carlo simulation of $pd \to {}^3\mathrm{He}\pi^0\pi^+\pi^-$ or by fitting the data to a Gaussian peak on a polynomial background. The difference in the numbers of ω obtained in the two ways is between 2% and 15%.

In Fig. 3, the angular dependence of the ω cross section at 1450 MeV is shown by the filled circles. These have been normalised by an arbitrary factor to give an average value of unity. Our data are clearly consistent with an isotropic distribution. To investigate the situation further, the same exercise was undertaken for events outside the peak region, i.e., $700 < MM({}^3\mathrm{He}) <$

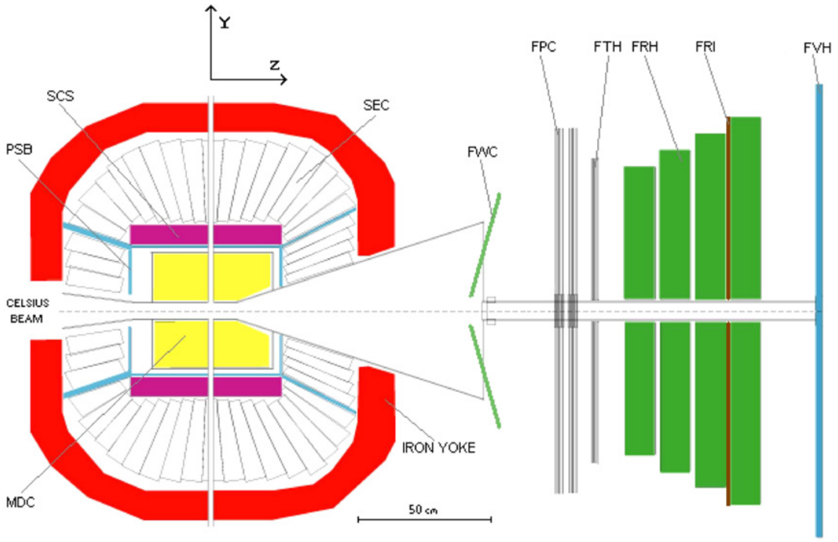

Fig. 1. Side view of the CELSIUS/WASA detector setup. The CELSIUS beam pipe runs horizontally and the target pellets are injected downwards through the vertical pipe.

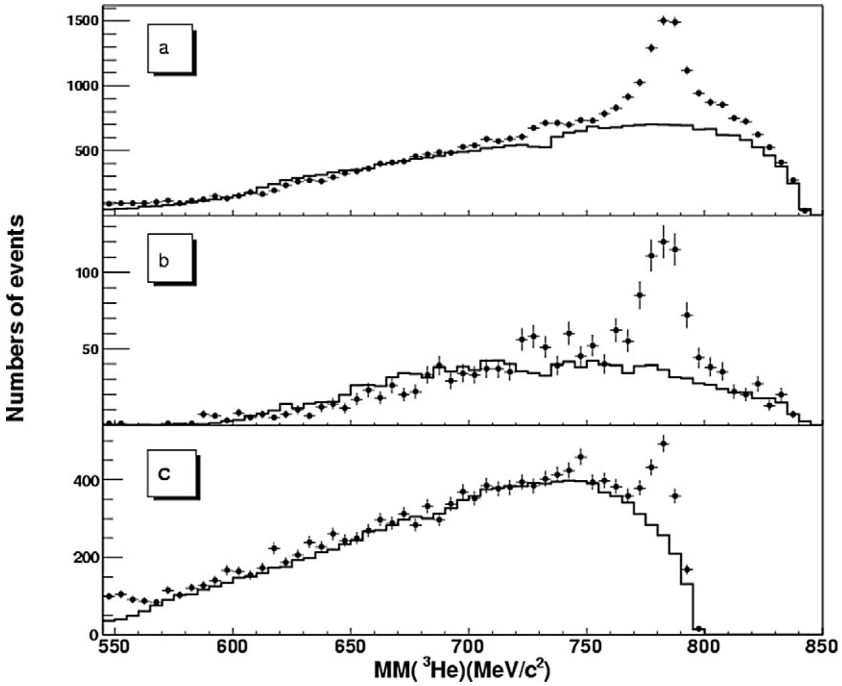

Fig. 2. (a) The points show the missing mass distribution from all 1450 MeV data that fulfill the criteria optimised for the selection of $pd \to {}^3\mathrm{He}(\omega \to \pi^0\pi^+\pi^-)$ events, as explained in the text. The histogram represents a Monte Carlo simulation of the $pd \to {}^3\mathrm{He}\pi^0\pi^+\pi^-$ reaction, assuming phase-space production. (b) The data show the missing mass distribution for the $pd \to {}^3\mathrm{He}(\omega \to \pi^0\gamma)$ event selection, while the histogram represents a phase-space simulation of the $pd \to {}^3\mathrm{He}\pi^0\pi^0$ reaction. (c) The same as (a), but for the 1360 MeV data.

750 MeV/c^2, where an isotropic distribution is likely due to the many available states for the multipion production as opposed to the $J^P = 1^-, T = 0$ state of the ω. After correcting for acceptance, the corresponding points in Fig. 3 have been shifted downwards by 0.5 to improve the readability in the figure. The statistics here are high and there is indeed little sign of any angular dependence. This gives some confidence that our setup and analysis does not introduce an artificial signal in the ω case.

A valuable consistency check can be obtained through the parallel study of the $\omega \to \pi^0\gamma$ decay channel. Although the low branching ratio of 8.7% leads to poor statistics, the signal-to-background ratio is better. This is due to the fact that all final-state particles, i.e., the ^{3}He and three photons, are measured with good acceptance.

In the event selection for this channel a ^{3}He plus three photons are demanded, where one photon pair has an invariant mass close to that of the π^0, and the invariant mass of all three photons should be larger than 600 MeV/c^2. The magnitude of the missing mass in the $^3\mathrm{He}3\gamma$ system must not exceed 100 MeV/c^2 and the difference between the direction of the missing momentum of the ^{3}He and that of the 3γ-system may not be larger than 20°. Finally, we apply the coplanarity cut on the laboratory azimuthal angles: $160^\circ < |\phi_{\mathrm{lab}}({}^3\mathrm{He}) - \phi_{\mathrm{lab}}(3\gamma)| < 200^\circ$.

The above conditions give an acceptance of 19% (18%) at 1450 (1360) MeV and the data fulfilling these criteria are shown in Fig. 2(b). The main background channel is $pd \to {}^3\mathrm{He}\pi^0\pi^0$ which, despite the low acceptance of only 1.8% for the given cuts, contributes significantly due to the high production cross section.

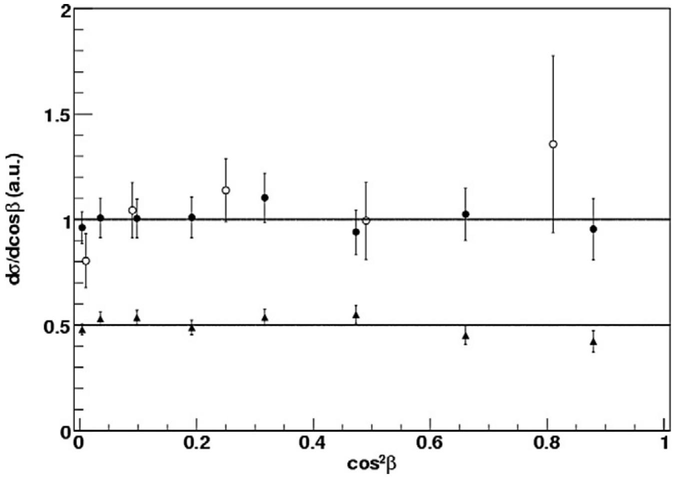

Fig. 3. The filled circles represent the differential cross section for $pd \to {}^3\mathrm{He}(\omega \to \pi^0\pi^+\pi^-)$ at 1450 MeV as a function of $\cos^2\beta$, where β is the angle between the normal to the ω decay plane and the proton beam direction. The data are arbitrarily normalised so that their average is unity, as indicated by the horizontal line, and the error bars are purely statistical. The non-filled circles show the corresponding cross section for the $pd \to {}^3\mathrm{He}(\omega \to \pi^0\gamma)$ channel, where β' now is the angle between the π^0 and the incoming proton. Both cross sections have been corrected for acceptance and are normalised using the identical overall factor. The triangles represent the $\cos^2\beta$ distribution for $pd \to {}^3\mathrm{He}\pi^0\pi^+\pi^-$ for events with $700 < MM({}^3\mathrm{He}) < 750\ \mathrm{MeV}/c^2$. The points were normalised to unity but then shifted downwards by 0.5 to improve the readability.

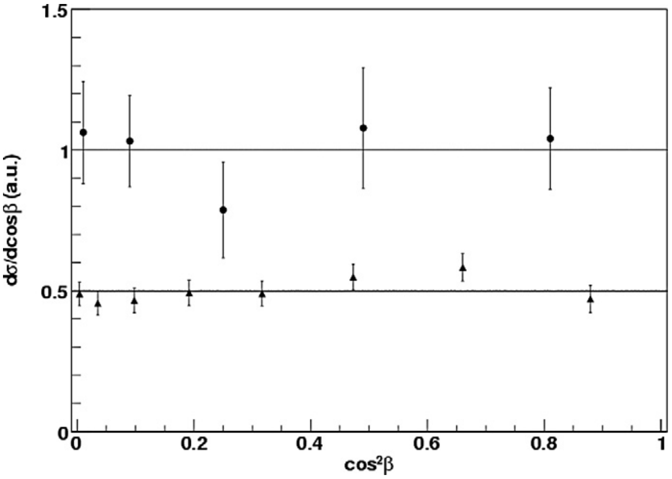

Fig. 4. The differential cross section for $pd \to {}^3\mathrm{He}(\omega \to \pi^0\pi^+\pi^-)$ at 1360 MeV. As in Fig. 3, the data have been arbitrarily normalised to give an average of unity. In addition to the statistical uncertainties shown, there are uncertainties in the background subtraction of between 18% and 30%. The three-pion background from the region $700 < MM({}^3\mathrm{He}) < 750\ \mathrm{MeV}/c^2$ is also shown, normalised to unity and shifted downwards by 0.5.

The corresponding angle for the polarisation study in the $\omega \to \pi^0\gamma$ channel is that of the π^0 or the γ in the ω rest frame with respect to the incoming proton beam. Denoting this angle by β', the angular distribution is expected to be of the form

$$\frac{\mathrm{d}\sigma(\omega \to \pi^0\gamma)}{\mathrm{d}\cos\beta'} \propto (1+\rho_{00}) - (3\rho_{00}-1)\cos^2\beta'. \qquad (2)$$

The difference in the structure of this equation and that of Eq. (1) is due to the fact that we are here describing the direction of one pion rather than that of the normal to a decay plane.

Since the statistics are smaller than for the three-pion decay, the data were divided into five regions in $|\cos\beta'|$. The number of ω candidates in each region was also obtained by plotting the missing mass of the ^{3}He and subtracting the background, both by using fitted Monte Carlo simulations of $pd \to {}^3\mathrm{He}\pi^0\pi^0$ and by fitting a Gaussian peak plus a polynomial. The differences in this case are typically 2–25%. After correcting for acceptance, branching ratio and bin size, we normalise using the *identical* factor to that employed in the $\omega \to \pi^0\pi^+\pi^-$ case. The good agreement in normalisation between the two decay channels, seen in Fig. 3 at 1450 MeV, shows that the relative cut efficiencies and other systematic effects are well understood. The data are also consistent with isotropy, with a $\chi^2/ndf = 1.02$, though with much larger error bars than for the three-pion channel.

The corresponding analysis at 1360 MeV is made much more difficult by the relatively large width of the ω. This becomes more important as threshold is approached since the high mass tail of the ω cannot then be produced and this leads to an asymmetric peak. The background fitting is also more complicated since the continuum ends under the ω peak and, furthermore, the signal-to-background ratio is smaller than at 1450 MeV. It is seen from Fig. 2(c) that, within the interval $750 < MM({}^3\mathrm{He}) < 800\ \mathrm{MeV}/c^2$, the ratio is $1:5$ compared to the $1:3$ in the 1450 MeV case. In addition, more beam time was taken at 1450 than at 1360 MeV so that there are both higher systematic and statistical uncertainties at this energy.

The statistics at 1360 MeV allow for a division of the $\omega \to \pi^0\pi^+\pi^-$ data into only five regions of $|\cos\beta|$ but, apart from this, the procedure for extracting the differential cross section, shown as a function of $\cos^2\beta$ in Fig. 4, is exactly the same as that at 1450 MeV. The systematic uncertainties from background subtraction are between 18% and 30%. Within the much larger error bars, the data are consistent with isotropy. This is also the case for the three-pion background, selected in this case for $700 < MM({}^3\mathrm{He}) < 750\ \mathrm{MeV}/c^2$. Regarding the $\omega \to \pi^0\gamma$ decay channel, the statistics at 1360 MeV are too poor to enable an investigation.

The angle between the π^0 from the $\omega \to \pi^0\pi^+\pi^-$ decay and the incoming proton has also been studied. In this case the distribution should be described by Eq. (2) and so one effectively loses a factor of two in sensitivity to the polarisation due to the larger constant factor in the equation compared to Eq. (1). The angular distribution of the π^0 is consistent with isotropy at both energies.

The angular dependence of the $\omega \to \pi^0\pi^+\pi^-$ data shown at 1450 and 1360 MeV in Figs. 3 and 4, respectively, have been fitted by straight lines to extract the values of ρ_{00} on the basis of Eq. (1). In this way we obtain $\rho_{00} = 0.33 \pm 0.05$ at 1450 MeV and $\rho_{00} = 0.34 \pm 0.10$ at 1360 MeV. The errors here are statistical but it is clear that the deviation from an unpolarised value of $\frac{1}{3}$ must be quite small. Some confirmation of this is found at 1450 MeV through the study of the $\omega \to \pi^0\gamma$ data, which gives $\rho_{00} = 0.14 \pm 0.14$. The uncertainty in this case is much larger than for the three-pion channel, due mainly to the poorer statistics that forced the reduction in the number of $|\cos\beta|$ intervals. It should be noted though that the obtained deviation from the unpolarised $\rho_{00} = \frac{1}{3}$ is here in the opposite direction from that found at MOMO for the ϕ meson, having $\rho_{00} = 0.82 \pm 0.05$ [5].

In order to test whether the ω polarisation depends upon its production angle θ^*_ω in the overall CM system, the $\omega \to \pi^0\pi^+\pi^-$ data at 1450 MeV were divided into three sub-samples with respect to $\cos\theta^*_\omega$. In all three regions the results were consistent with ω being unpolarised. Specifically, for

$$\cos\theta^*_\omega < -0.5 \quad \Rightarrow \quad \rho_{00} = 0.29 \pm 0.08,$$

$$|\cos\theta^*_\omega| < 0.5 \quad \Rightarrow \quad \rho_{00} = 0.37 \pm 0.06,$$

$$\cos\theta^*_\omega > 0.5 \quad \Rightarrow \quad \rho_{00} = 0.30 \pm 0.09.$$

In this work we have shown that, within error bars, the ω produced in the $pd \to {}^3\mathrm{He}\omega$ reaction are unpolarised with respect to the incident proton beam direction. However, it is also of interest to study the polarisation in the helicity frame [15], where the reference axis is provided by the direction of the ^{3}He. Unlike the Jackson angle distribution, this cross section must be flat near threshold since only *s*-waves then contribute. Although the sensitivity to the polarisation is small, it is reassuring that the helicity distribution is completely consistent with isotropy at both beam energies.

The contrast between our result for the ω polarisation and that of the ϕ in the $pd \to {}^3\mathrm{He}\omega/\phi$ reactions could hardly be more striking since the MOMO Collaboration reported a polarisation along the proton beam direction corresponding to almost complete alignement [5]. Although the ϕ production was carried out slightly closer to threshold than the ω production, it nevertheless suggests strongly that the reaction mechanism for the production of the two mesons must differ significantly in their details. An OZI inspired interpretation of the difference in the ϕ and ω production near threshold therefore seems to fall short, both on the account of the new polarisation data as well as the previously reported cross section data. It is therefore likely that the reactions are much more influenced by nuclear and mesonic degrees of freedom rather than hadron properties at the quark level.

It would be instructive if the ω and ϕ polarisations could be compared in other low energy hadronic reactions. However, it should be noted that conservation laws require that these vector mesons must be completely polarised, with $\rho_{00} = 0$ along the beam direction, when they are produced in $pp \to pp\omega/\phi$ or $pn \to d\omega/\phi$ at threshold [6,7,16]. Hence any test here would have to be carried out at higher energies.

In summary, from the study of both the $\omega \to \pi^0\pi^+\pi^-$ and $\omega \to \pi^0\gamma$ decay channels in the $pd \to {}^3\mathrm{He}\omega$ reaction, we have shown that the ω mesons are essentially unpolarised near threshold. The relative cross sections obtained using the two channels gives results that are consistent within statistics. However, the absolute values of the cross section depend upon the luminosity and other elements that cancel in this ratio. The evaluation of these values is the subject of an ongoing study, which will give the differential cross section as a function of the ω polar angle [17].

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