Vector meson angular distributions in proton-proton collisions

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The resonance model is used to analyze the \(\omega\) and \(\phi\) meson angular distributions in proton-proton collisions at \(\sqrt{s} = 2.83\) and 2.98 GeV. The assumption of dominant contributions from \(N^*(1720)\) and \(N^*(1900)\) resonances which both have, according to the \(pN\) scattering multichannel partial-wave analysis and/or quark models predictions, are expected to be important. The \(\omega\)-meson angular distribution at \(\sqrt{s} = 2.83\) GeV. The angular distribution at \(\sqrt{s} = 2.98\) GeV can be reproduced assuming the dominance of \(N^*(2000)\) and \(N^*(1900)\). The experimental \(\phi\)-meson angular distributions do not show any asymmetry which requires the existence of a massive negative-parity spin-half resonance. This resonance could be identified with the \(N^*(2000)\).

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The COSY-TOF collaboration\(^1\) has recently measured the \(\omega\)-meson angular distribution in proton-proton collisions at an excess energy \(\epsilon = 173\) MeV \((\sqrt{s} = 2m_p + m_\omega + \epsilon)\) above the \(\omega\) threshold. Earlier, angular distribution of \(\omega\)-mesons have been measured by the DISTO collaboration\(^2\) at an energy excess of \(\epsilon = 320\) MeV. The \(\phi\)-meson distribution is found to be consistent with a flat distribution, whereas the \(\omega\)-mesons at the both values of \(\epsilon\) are peaked towards the beam directions.

The cross sections of vector mesons production enter as an input into transport models for the dilepton emission in heavy-ion collisions\(^3\).\(^4\).\(^5\). The direct \(\rho(\omega) \rightarrow e^+e^-\) decay channels give important contributions to the dilepton production. The detector efficiency depends thereby on the absolute value and direction of momentum of the dilepton pairs. Hence, the angular distribution of the vector mesons produced in nucleon-nucleon collisions affects the counting rate of the dilepton pairs which makes it necessary to keep the angular dependence of the production cross sections theoretically under the control.

The HADES experiment\(^6\) is presently studying the dilepton spectra in the same energy region in great detail. The pion production is the best known inelastic reaction in \(pp\) collisions. A model independent partial-wave analysis of the experimental data has been performed up to \(\epsilon_x = 20\) MeV above the threshold\(^7\). The pion angular distribution shows an increasing anisotropy with energy.

The meson production in \(pp\) collisions has previously been analyzed using the OBEP models\(^8\). The most of the realistic nucleon-nucleon interactions models have the \(\Delta(1232)\) isobar included as a special degree of freedom. It is naturally to assume that with increasing the energy other nucleon resonances also become important. The resonance model\(^10\),\(^11\) as a first step treats matrix elements of the higher-mass resonance production as phenomenological constants fixed by fitting the available inelastic cross sections. Such an approach is suitable to obtain estimates for the importance of various meson production channels and it allows to perform simulations of heavy-ion reactions in which the role of nucleon resonances is important. The resonance model fits the \(\rho\), \(\omega\), and \(\phi\) total production cross sections rather well\(^12\),\(^13\),\(^14\).

The decay rates of nucleon resonances into the dilepton pairs and vector mesons with the same invariant mass coincide up to an overall kinematic factor. The \(\Delta(1232)\) Dalitz decay is one of the major sources of dileptons in heavy-ion collisions at intermediate energies\(^3\),\(^4\),\(^5\). The first correct calculation of that decay was given only recently\(^15\), whereas kinematically complete expressions for Dalitz decays of other high-spin resonances were given in\(^16\). In this paper, we analyze the angular distributions of the \(\omega\)- and \(\phi\)-mesons in proton-proton collisions within the framework of the resonance model.

According to the resonance model, the dominant contributions to the meson production cross sections originate from reactions \(pp \rightarrow pN^*\) followed by subsequent decays \(N^* \rightarrow p\omega(\phi)\). The first reaction takes place at \(m_p + m_{N^*} \leq \sqrt{s}\), while the second reaction with e.g. an \(\omega\) production, takes place at \(m_p + m_\omega \leq m_{N^*}\). These inequalities can be combined to give \(1.72 \leq m_{N^*} \leq 1.89\) GeV and \(1.72 \leq m_{N^*} \leq 2.05\) GeV, respectively, for the COSY-TOF and DISTO experimental conditions. The \(\phi\)-meson production is sensitive to the mass interval \(1.96 \leq m_{N^*} \leq 2.04\) GeV.

Either a nucleon resonance falls into these intervals with its pole masses or, if not, it can have a Breit-Wigner leaking...
into the corresponding mass intervals. In the present work we will focus mainly on the first possibility. According to Particle Data Group \cite{17} the following resonances can be important: $N^*(1720)^{3/2}_2$, $N^*(1900)^{3/2}_2$, $N^*(1990)^{3/2}_2$, and $N^*(2000)^{3/2}_2$. The negative-parity resonances have masses below 1.72 GeV, while $\Delta^*$ resonances do not contribute to the $\omega$ and $\phi$ production due to the isotopic symmetry.

At $\epsilon = 173$ MeV the resonances $N^*(1720)^{3/2}_2$ and $N^*(1900)^{3/2}_2$ appear at different kinematic conditions: In the $N^*(1720)$ decay, the $\omega$ is mainly produced at rest. In the $pp$ collisions, the $N^*(1720)$ is produced with a velocity $v \sim 0.26$. The $\omega$-meson angular distribution coincides therefore with the angular distribution of the $N^*(1720)$ resonance. The maximal angular momentum for the system $pN$ is produced at rest. In the experiments \cite{1,2}, the resonance spin is therefore correlated with the beam direction. The initial protons in the experiments \cite{1,2} are not polarized. The resonance spin is therefore correlated with the beam direction.

Let us first consider the $N^*(1900)$. The angular wave function of the $p\omega$ system, appearing due to a $J^P$ resonance decay, has the form

$$\Psi(n_\omega) \sim \sum_{SL} A_{SL} C^{JJ_z}_{j-j_z} \sum_{\mu} C^{SS_{\mu}} \sum_{LL_z} Y_{LL_z}(n_\omega).$$

The Clebsch-Gordan coefficients $C^{JJ_z}_{j-j_z}$ are defined with the PDG phase conventions \cite{17}. The partial-wave decomposition includes the total spins $S = 1/2$ and $3/2$ of the $p\omega$ system and the $p\omega$ orbital momenta $L$ such that $|J - S| \leq L \leq J + S$. Parity conservation gives a selection rule $P = (-1)^{L+1}$. The amplitudes $A_{SL}$ for different resonances are extracted from the $\pi N$ inelastic scattering data and/or predicted by the quark models (for a review see \cite{17}).

The $pN^*(1900)$ system appears close to the threshold in the $S$ state ($\eta \sim 0$). The initial protons have therefore the total angular momentum $j = 1$ or 2 and positive parity. The state $1^+$ is forbidden by the Pauli principle, so the only possibility is $j^P = 2^+$ which is the $1d_2$ state for the initial protons. The higher states are classified in Table 1.

The transition amplitude $pp \rightarrow pN^*(1900)$ can be obtained constructing a rotational scalar out of the initial-state spherical harmonics $Y_{j j_z}(n_p)$, where $n_p$ is the unit vector in direction of the proton beam. The final-state $pN^*(1900)$ spin wave function reads:

$$M_{f1} \sim C^{jj_z}_{j\frac{3}{2} j_z} Y_{jj_z}(n_p).$$

Now, let the quantization axis of the angular momentum be parallel to the proton beam $n_p$. The only non-vanishing component of the initial-state wave function is $j_z = 0$. The orbital momentum is perpendicular to the beam and its projection to the beam direction is equal to zero. The polarization matrix of a spin-$J$ resonance becomes then diagonal. The diagonal elements equal

$$\rho_{J_zJ_z} = |C^{jj_z}_{J_z\frac{1}{2}J_z}|^2,$$

and so $\rho_{J_zJ_z} = 1/2$ at $J_z = \pm 1/2$ and, for a higher spin resonance, $\rho_{J_zJ_z} = 0$ at $|J_z| \geq 3/2$. Eq.(3) is valid for all even-$j$ positive-parity initial states. Spin-half resonances are therefore produced unpolarized near threshold, whereas higher spin resonances, including the $N^*(1900)$, are polarized.

| $j^P$ | $2j+1l_j$ |
|-------|-------------|
| $j^+$ even $\frac{1}{2}j_1$ |
| $j^-$ odd $\frac{3}{2}j_1$ |
| $j^+$ odd forbidden |
| $j^-$ even $\frac{3}{2}(j-1) \oplus \frac{3}{2}(j+1)$ |

### Table I: $jj$ states of two protons at $j \geq 1$ and their $2j+1l_j$ decompositions satisfying the Pauli principle.
The angular distribution of the $\omega$-mesons produced through the $N^*(1900)\rightarrow p\omega$ decay can be found by weighting the polarization matrix (3) with the modulus squared of the $p\omega$ angular function summed over the final-state $p\omega$ spin projections:

$$\frac{d\sigma}{d\Omega} \sim \sum_{J_z} \rho_{J_z J_z} \sum_{SS_z} \sum_{L} A_{LS} C_{SS_zLL_z}^{J_z J_z} Y_{LL_z}(\hat{n}_\omega)^2.$$  \hspace{1cm} (4)

The coefficient $C_{SS_zLL_z}^{J_z J_z}$ entering the $p\omega$ wave function (cf. Eq. 3) gives after summation over the $\mu$ and $\mu_\omega$, a decoherent sum over the total spin and spin projection of the $p\omega$ system.

The partial-wave amplitudes $A_{LS}$ of the $N^*(1900)\rightarrow p\omega$ decay are extracted by Manley and Saleski [18] from $\pi N$ multichannel partial-wave analysis and/or quark model predictions by Konik [19], Capstick and Roberts [20], and Stassart and Stancu [21] and/or predicted by the extended Vector Meson Dominance (eVMD) model [16]. The resulting angular distributions are shown in Fig. 1 together with the experimental data [1].

The models [16, 18, 19] predict a dominant $p_{1/2}$ wave with an angular dependence $\sim 1 + 3\cos^2\theta_\omega$, very close to the experiment. The models [16, 18, 19, 21] are in very good agreement with the data. Capstick and Roberts [21] report a vanishing $p_{1/2}$ amplitude and large errors for the $p_{3/2}$ and $f_{3/2}$ amplitudes. The dominance of the $f_{3/2}$ transition does not contradict to the model [20] and to the experimental data [1]. This amplitude is shown on Fig. 2 as $CR[f_{3/2}]$. The $p_{3/2}$ transition can apparently be excluded.

If the $N^*(1900)$ resonance would be unpolarized, it could produce an isotropic $\omega$-meson distribution. The distributions plotted on Fig. 1 within the resonance model, are a consequence of the selection rules, the kinematic conditions, and the partial-wave content of the $N^*(1900)$ decay amplitude.

The $N^*(1900)$ width equals $\Gamma_{N^*}^{el} = 500 \pm 80$ [17]. In general, resonances are produced off-shell with invariant masses away from the pole mass. The off-shell $N^*(1900)$’s move with finite velocities which leads to a smearing of the $\omega$ angular distribution compared to the $N^*(1900)$ decays at rest. To estimate this effect, let us compare velocities of the $\omega$ in the $N^*(1900)$ rest frame and of the $N^*(1900)$ in the c.m. frame of two initial protons. For $\epsilon = 173$ MeV, we have $v_\omega = 0.46$ and $v_{N^*} = 0$ at $m_{N^*} = 1.9$ GeV and $v_\omega = 0$ and $v_{N^*} = 0.26$ at $m_{N^*} = 1.72$ GeV. The $\omega$ and $N^*$ velocities are equal $v_\omega = v_{N^*} = 0.23$ at $m_{N^*} = 1.76$ GeV, i.e. a 40 MeV above the $N^* \rightarrow p\omega$ decay threshold. The approximation in which the $N^*(1900)$ is treated as a particle at rest is therefore reasonable. Hence, we do not expect a large smearing effect due to the off-shell production of the $N^*(1900)$.

Let us now discuss the $N^*(1720)$. The maximum $pN^*$ angular momentum at the excess energy $\epsilon = 173$ MeV was estimated as $\sim \eta = 3.4$. Hence the $pN^*$ system can appear in orbitally excited states. The partial-wave content of

FIG. 1: The angular distribution of the $\omega$-mesons in the c.m. frame of the colliding protons assuming the reaction goes through the $N^*(1900)\rightarrow p\omega$ resonance. The experimental data from COSY-TOF [1] were obtained for an excess energy $\epsilon = 173$ MeV. The $p_{1/2}$ contribution $\sim 1 + 3\cos^2\theta_\omega$ in the $p\omega$ decay of the $N^*(1900)$ is dominant according to the models MS [18], K [19], and eVMD [16]. The predictions of the models CR [20] and SST [21] are shown as well.
the transition $pp \rightarrow pN^*$ is unknown. A dominant $S$-wave component can immediately be excluded since it produces an isotropic $N^*(1720)$ and correspondingly also an isotropic $\omega$ angular distribution. Let us check if $L = 1$ and $L = 2$ waves are dominant components.

There exist eight $L = 1$ amplitudes: $3p_0^3P_0$, $3p_1^3P_1$, $3p_2^3P_1$, $3p_1^5P_1$, $3p_2^5P_2$, $3f_2^3P_2$, $3f_2^5P_2$, and $3f_3^5P_3$ with quantum numbers $2s + 1L_j$, $2S + 1L_j$ where $s$, $l$, and $j$ are the total spin, orbital momentum, and total angular momentum of the initial $pp$ state. $S$ and $L$ are the total spin and orbital momentum of the final $pN^*$ state. The angular distributions for the isolated transitions can be calculated from

$$\frac{d\sigma}{d\Omega} \sim \sum_{L_s L} C_{s_j s_0}^{\jmath j} C_{SS_{LL}}^{\jmath j} \mathcal{Y}_{LL_s}(\mathbf{n}_w)^2. \quad (5)$$

They are plotted on Fig.2. Since in the resonance rest frame the $\omega$-meson is produced at rest, the $\omega$ momentum has in the $pp$ c.m. frame the same direction as the $N^*(1720)$ momentum. Thus we have replaced in $\mathbf{n}_{N^*}$ with $\mathbf{n}_\omega$.

The wave Nos. 6, 8, 3, and 2 with quantum numbers $3f_2^3P_2$, $3f_2^5P_2$, $3p_2^3P_1$, and $3p_1^5P_1$ resemble qualitatively the measured distribution, but yet no conclusions can be drawn on the actual importance of these waves. The ratio between maximal and minimal values of the differential cross section for those waves is below a factor of 3, whereas the experimental ratio is close to a factor of 4. Therefore the $N^*(1900)$ alone gives a stronger angular dependence, being in slightly better agreement with the data.

There exist four $L = 2$ transition amplitudes: $1d_2^3P_0$, $1s_0^5D_0$, $1d_2^5D_2$, and $1g_4^5D_4$. The corresponding $\omega$-meson angular distributions are shown in Fig.2. The $1g_4^5D_4$ distribution resembles the experimental one, but has a plateau at $\cos \theta_\omega \sim 0$. The pattern of other waves is quite different from the observed one. The transitions $L = 0$ and $L = 1$ Nos. 1, 4, 5, and 7 and $L = 2$ Nos. 1, 2, and 3 can apparently be excluded as dominant ones. The other four $P$-waves and the one $D$-wave transition can be large. These conclusions, however, are not stable against effects from the finite $N^*(1720)$ width of $\Gamma_{N^*}^{tot} = 150 \pm 50$ MeV.\hfill 

The off-shell $N^*(1720)$ production results into an $\omega$ distribution representing a convolution of the $N^*(1720)$ and $\omega$ angular distributions. As we estimated, at $m_{N^*} = 1.76$ GeV the resonance and $\omega$ velocities are equal, so the $N^*(1720)$ tail $m_{N^*} \geq 1.76$ GeV generates roughly the $N^*(1720) \rightarrow N\omega$ decay distribution, whereas the invariant masses $1.72 \leq m_{N^*} \leq 1.76$ GeV correspond to one of the distributions plotted on Fig.2. The domain of 40 MeV above the $\omega$ threshold is not large compared to the resonance width. Hence the pattern of the decay $N^*(1720) \rightarrow N\omega$ is important. According to $14, 15$, the $p_{1/2}$ wave $\sim 1 + 3\cos^2 \theta_\omega$ of the $N^*(1720) \rightarrow N\omega$ decay is dominant. Other authors give negligible $\omega$ couplings for the $N^*(1720)$.

The $N^*(1720)$ production cross section is parameterized as an $S$-wave process.\hfill 

This resonance provides $10\% - 20\%$ of the total $pp\omega$ cross section.\hfill 

Such a value does not contradict to the $\omega$-meson angular distribution even in the sharp resonance limit. The angular distribution data do not provide stringent constraints to the $S$-wave part of the $N^*(1720)$ production.

The $N^*(1900)$ is reliably predicted by quark models, but has currently a lower experimental status (***) than the $N^*(1720)$. The $N^*(1900)$ cross section is unknown and its contribution to the vector mesons production is set equal to zero $12, 13, 14$. In the region $\sqrt{s} \sim 2.8$ GeV the vector meson production, according to $12, 13, 14$, is determined by tails of resonances of smaller masses and by the $N^*(1900)$. If we attribute the total cross section to the $N^*(1900)$ alone, we get $\sigma(pp \rightarrow pN^*(1900))B(N^*(1900) \rightarrow p\omega) \sim 30$ mb. Using the estimate of $14$, $\Gamma_{N^*\omega}^{tot} \sim 60$ MeV and the PDG value of $\Gamma_{N^*\omega}^{tot} \sim 500$ MeV, one gets $\sigma(pp \rightarrow pN^*(1900)) \sim 0.3$ mb at $\sqrt{s} \sim 2.8$ GeV. This is below the $s$-wave unitarity limit of $4\pi/k^2 \sim 4$ mb.

Under the conditions of the DISTO experiment, we have $u_\omega = 0$ and $v_{N^*} = 0.35$ at $m_{N^*} = 1.72$ GeV and $v_\omega = 0.56$ and $v_{N^*} = 0$ at $m_{N^*} = 2.05$ GeV. The resonance and $\omega$ velocities at $\epsilon = 320$ MeV are equal to each other $v_\omega = v_{N^*} = 0.3$ at $m_{N^*} = 1.8$ GeV.

The approximation $u_\omega$ is good for the resonance $N^*(1720)$. The angular distribution due to the $N^*(1720)$ production is the same as in Fig.2. The $L = 2$ wave $1g_4^5D_4$ is the only wave that fits the DISTO $\omega$-meson data. The approximation $v_{N^*}$ is good for the resonances $N^*(1900)$, $N^*(1900)$, and $N^*(2000)$. The angular distribution due to the $N^*(1900)$ production is the same as in Fig.1. The pattern of the distribution is correct, but the $N^*(1900)$ does not develop a plateau at $\cos \theta_\omega \sim 0$ which is required by the DISTO data. The angular distributions of the $N^*(1900)$ and $N^*(2000)$ are shown on Fig.3. The model gives results close to the observations in both cases, the other models give reasonable angular dependences in the case of a $N^*(1900)$ dominance but stand in contradiction to a possible $N^*(2000)$ dominance.

The $\phi$-meson angular distribution at $\sqrt{s} = 2.98$ GeV, i.e. 85 MeV above the $\phi$-meson production threshold, is found to be consistent with an isotropic distribution.\hfill 

The maximal $\phi$ momentum can be estimated in the c.m. frame to be $p_\phi^{max} = 0.33$ GeV and the maximal $\phi$ orbital momentum relative to the $pp$ pair $\sim \eta_\phi = p_\phi^{max}/m_\pi = 2.4$. The $S$-wave $\phi$-meson state allows $j^p = 1^-$ final states, whereas the higher orbital states are apparently excluded by the data which is somewhat surprising.
FIG. 2: The normalized $L = 1$ and $L = 2$ angular distributions of the $N^*(1720)^{1+}$ resonance in transitions $^{2s+1}_{j}l^{2S+1}L_{j}$, where $s, l, j$ are the total spin, orbital momentum, and total angular momentum in the initial $pp$ state. $S$ and $L$ are the total spin and orbital momentum in the final $pN^*$ state. The numbers 1 to 8, attached to the $L = 1$ curves, correspond to the waves $^3p_0^3P_0$, $^3p_1^3P_1$, $^3p_2^3P_2$, $^3f_0^3P_2$, $^3f_1^3P_2$, and $^3f_2^3P_3$, respectively. The numbers 1 to 4, attached to the $L = 2$ curves, correspond to the waves $^1d_2^3D_2$, $^1s_0^5D_0$, $^1d_2^5D_2$, and $^1g_4^5D_4$.

FIG. 3: The angular distribution of the $\omega$-mesons in the c.m. frame of the colliding protons assuming that the reaction proceeds through $N^*(1990)^{2+}$ and $N^*(2000)^{2+}$ decays. The models K [19], CR [20], SST [21], and eVMD [16] are compared to the DISTO data at $\sqrt{s} = 2.98$ GeV [2].

The $\omega - \phi$ mixing is sufficient to reproduce the $\phi$-meson production cross section at $\sqrt{s} = 2.98$ GeV [14]. Such a mechanism, owing to the mass dependence of the $NN^*\omega$ coupling constants, yields in the nucleon resonance decays identical angular distributions for $\phi$- and $\omega$-mesons. To construct a $1^- \rightarrow 1^- \rightarrow 1$ final state out of the proton and a resonance in a $S$-wave, one needs negative-parity resonances. The well established negative-parity resonances $N^*(1535)^{-1}_{1}^{(1)}$, $N^*(1650)^{-2}_{1}^{(1)}$, and $N^*(1700)^{-2}_{1}^{(2)}$ with non-vanishing couplings to $\omega$-mesons have low masses and can only contribute to the reaction through their Breit-Wigner tails. These resonances have dominant $s_{1/2}$ branchings [10,11] and thus their tails would produce an isotropic cross section. The resonances $N^*(2090)^{-3}_{1}^{(1)}$ and $N^*(2080)^{-3}_{1}^{(2)}$ are listed by PDG [17] with ratings (*) and (**), respectively. Quark models predict several negative-parity states with masses around 2000 MeV but according to ref. [20] the $s_{1/2}$ decays of these resonances are subdominant.

The $J = \frac{1}{2}$ resonances in the $j^P = 1^-$ state give isotropic distributions. In the reference frame where the quantization axis of the angular momentum is parallel to the proton beam, the polarization matrix of the spin-$J$ resonance can be
These two near-threshold processes appear to be different with respect to the convergence rate of the partial-wave expansion. The isotropic distribution observed by the DISTO collaboration can be interpreted as an evidence for a strong dominance of the $N(1232)$ system [23]. In the $NN\pi$ system e.g. at $\sqrt{s} = 20$ MeV [8]. The value of $\eta_\pi = p_{\pi}^{max}/m_\pi$ is small and varies in the limits 0.07 - 0.5. In the limit $\eta_\pi \rightarrow 0$, only the $S$-wave survives, so the distribution must be symmetric. The large $S$-wave of the $NN\pi$ system e.g. at $\eta_\pi \sim 0.22$ implies an almost symmetric angular distribution which is reported [8]. Within the resonance model, the dominance of the $S$-wave implies apparently the dominance near the threshold of tails of the negative-parity nucleon resonances produced in an $S$-wave together with the nucleon. The importance of heavy resonances near the pion threshold is emphasized in [22]. With increasing $\eta_\pi$, the pion distribution develops an anisotropy that becomes essential at $\eta_\pi \sim 0.5$. It can be attributed at least partially to the $\Delta(1232)$ which appears in the $S$-wave with another nucleon and generates the pion distribution $\sim 1 + 3\cos^2\theta_\pi^*$, the same as the $\omega$-meson distribution in the $p_1/2$ wave with the proton, since the $\Delta(1232)$ has the same $p_1/2$ decay mode and the same spin as the $N^*(1900)$ resonance. Note that Eq. 4 has no dependence on the constituent spins, only the total spin $S$ is important. At $\epsilon_\pi = 20$ MeV, the ratio between the $j^p = 1^-$ wave cross section that gives the flat distribution and the $j^p = 2^+$ wave cross section that gives the $\sim 1 + 3\cos^2\theta_\pi^*$ distribution can be estimated from the angular distribution alone to give $\sim 3 : 2$ which is almost two times lower than the ratio of $\sim 5 : 2$ given by [8]. There is therefore space for contributions due to the asymmetry of other resonances and/or for higher orbital states of the $N\Delta(1232)$ system [22]. In the $pp \rightarrow pp\phi$ reaction, while the $\phi$-meson is nonrelativistic, the maximal value of the orbital momentum $\sim \eta_\phi = p_{\phi}^{max}/m_\pi$ is several times larger than in the pion production studied in [8]. These two near-threshold processes appear to be different with respect to the convergence rate of the partial-wave expansion. The isotropic distribution observed by the DISTO collaboration can be interpreted as an evidence for a strong dominance of the $N^*(2090)\frac{1}{2}^-$ or any other spin-half negative-parity resonance. We would otherwise expect on the pure kinematic grounds an isotropic angular distribution starting from the $\omega$ production threshold of $\sqrt{s_\omega} = 2.90$ GeV up to 2.92 GeV where $\eta_\phi \leq 1$ and an increased anisotropy beyond 2.92 GeV where higher orbital waves should come into play.

The angular differential cross sections provide sensitive tests for the reaction mechanisms. The present data do
not offer enough information for a complete partial-wave analysis. The resonance model which we discussed can be considered as first step to construct a microscopic $NN \to NN^*$ transition potential using the $t$-channel exchange OBEP models or proposed recently an $s$-channel dibaryon exchange $NN$ interaction model [21].

The $N^*(1720)\frac{3}{2}^+$ and $N^*(1900)\frac{3}{2}^+$ resonances both have the dominant $p_{1/2}$ decay $N\omega$ modes. If velocities of these resonances in the c. m. frame of two protons are not high compared to the $\omega$ velocities in the $N^*$ rest frames, which is a good approximation also for a significant off-shell spectral part of the $N^*(1720)$, the $N^* \to N\omega$ decays produce an angular distribution very close to the COSY-TOF data. The mechanism involving these two resonances could be the dominant one in the $\omega$ production at $\sqrt{s} = 2.83$ GeV. The several $P$ and the one $D$ wave of the $NN^*(1720)$ system generate also $\omega$ patterns close to the experimentally observed one.

At $\sqrt{s} = 2.98$ GeV a dominance of $N^*(1900)\frac{5}{2}^+$ is also $N^*(2000)\frac{5}{2}^+$ within the model [20] gives a reasonable description of the DISTO angular distribution data. The resonance $N^*(1900)\frac{3}{2}^+$ at rest generates still the right pattern but without a plateau at $\cos\theta_\omega^c \sim 0$. The $N^*(1720)$ generates the right pattern through the $1^g_4^5D_4$ transition. The $\phi$-meson data can be explained by the dominance of the $N^*(2090)\frac{3}{2}^+$. It is not clear, however, why higher orbital states of the $\phi$ and, respectively, high-spin nucleon resonances which give anisotropic distributions should not be involved in the $\phi$-meson production.

We formulated also a general theorem according to which from every $2^{s+1}l_j$ initial state of two unpolarized protons, spin-half nucleon resonances are produced in the threshold being unpolarized, whereas high-spin nucleon resonances are produced being polarized. The absence of any structure in the meson angular distribution indicates the possible dominance of a spin-half nucleon resonance, whereas the presence of a structure indicates the possible dominance of a $J \geq 3/2$ nucleon resonance.

A complete partial wave analysis requires angular distributions from experiments with polarized beams. At the moment several competitive mechanisms can explain the $\omega$-meson production data while the $\phi$-meson distribution cannot be interpreted so easily.

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