

Vector meson angular distributions in proton-proton collisions

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The resonance model is used to analyze the ω - and ϕ -meson angular distributions in proton-proton collisions at $\sqrt{s}=2.83$ and 2.98 GeV. The assumption of dominant contributions from $N^*(1720)_{\frac{3}{2}^+}$ and $N^*(1900)_{\frac{3}{2}^+}$ resonances which both have, according to the πN scattering multichannel partial-wave analysis and/or quark models predictions, dominant $p_{1/2}$ $N\omega$ decay modes yields the right pattern of the ω angular distribution at $\sqrt{s}=2.83$ GeV. The angular distribution at $\sqrt{s}=2.98$ GeV can be reproduced assuming the dominance of $N^*(2000)_{\frac{5}{2}^+}$ and $N^*(1900)_{\frac{3}{2}^+}$. The experimental ϕ -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 $N^*(2090)_{\frac{1}{2}^-}$.

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

The cross sections of vector meson production enter as an input into transport models for the dilepton emission in heavy-ion collisions [3–5]. 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 control.

The dilepton spectra in heavy-ion collisions at $T=1-5$ GeV/A were measured by the DLS collaboration [6]. The HADES experiment [7] 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 $\epsilon_\pi=20$ MeV above the threshold [8]. The pion angular distribution shows an increasing anisotropy with energy.

The meson production in pp collisions has previously been analyzed using the OBEP models [9]. Most of the realistic nucleon-nucleon interaction models have the $\Delta(1232)$ isobar included as a special degree of freedom. It is natural 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 one to per-

form simulations of heavy-ion reactions in which the role of nucleon resonances is important. The dominance of nucleon resonances in the intermediate states is equivalent to taking nucleon-meson final-state interactions into account [12]. The resonance model fits the ρ , ω , and ϕ total production cross sections rather well [5,12–14].

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 [3–5]. 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 Ref. [16]. In this paper, we analyze the angular distributions of the ω and ϕ 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 ω 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 ϕ -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 tail leaking into the corresponding mass intervals. In the present work we will focus mainly on the first possibility. According to the Particle Data Group (PDG) [17] the following resonances can be important: $N^*(1720)_{\frac{3}{2}^+}$, $N^*(1900)_{\frac{3}{2}^+}$, $N^*(1990)_{\frac{7}{2}^+}$, and $N^*(2000)_{\frac{5}{2}^+}$. The negative-parity resonances have masses below 1.72 GeV, while Δ^* resonances do not contribute to the ω and ϕ production due to the isotopic symmetry.

At $\epsilon=173$ MeV the resonances $N^*(1720)_{\frac{3}{2}^+}$ and $N^*(1900)_{\frac{3}{2}^+}$ appear at different kinematic conditions: In the $N^*(1720)$ decay, the ω is mainly produced at rest. In the pp

TABLE I. j^p states of two protons at $j \geq 1$ and their $^{2s+1}L_j$ decompositions satisfying the Pauli principle.

j^p	$^{2s+1}L_j$
j^+ even	1j_j
j^- odd	3j_j
j^+ odd	forbidden
j^- even	$^3(j-1)_j \oplus ^3(j+1)_j$

collisions, the $N^*(1720)$ is produced with a velocity $v \sim 0.26$. The ω -meson angular distribution coincides, therefore, with the angular distribution of the $N^*(1720)$ resonance. The maximal angular momentum for the system pN^* can be estimated as $\eta = p^*/m_\pi$, where p^* is the c.m. momentum in the final state, $1/(2m_\pi)$ is the strong interaction radius, and m_π is the pion mass. For $\epsilon = 173$ MeV, one has $\eta \sim 3.4$. One can expect that the partial-wave decomposition is truncated at a pN^* orbital momentum ~ 3 .

In the $N^*(1900)$ decay the ω is produced with velocity $v \sim 0.82$, whereas in the pp collisions the $N^*(1900)$ is produced mainly at rest. The angular distribution of the ω mesons coincides, therefore, with the corresponding ω distribution in the $N^*(1900)$ resonance decay. This means that the direction of the ω momentum is correlated with the resonance spin. The initial protons in the experiments [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

$$\Psi(\mathbf{n}_\omega) \sim \sum_{SL} A_{SL} C_{SS_z LL_z}^{JJ_z} C_{1/2 \mu_1 \mu_\omega}^{SS_z} Y_{LL_z}(\mathbf{n}_\omega). \quad (1)$$

The Clebsch-Gordan coefficients $C_{jj_z ll_z}^{JJ_z}$ are defined with the PDG phase conventions [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 πN inelastic scattering data and/or predicted by the quark models (for a review see Ref. [16]).

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 I.

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

$$\mathfrak{M}_{fi} \sim C_{1/2 \mu J_z}^{jj_z} Y_{jj_z}(\mathbf{n}_p). \quad (2)$$

Now, let the quantization axis of the angular momentum be parallel to the proton beam \mathbf{n}_p . The only nonvanishing com-

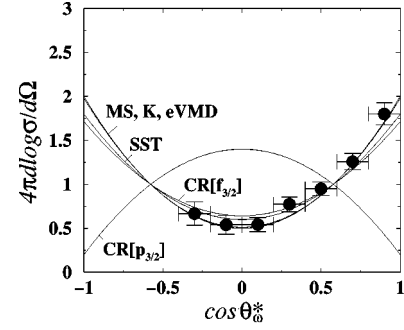


FIG. 1. Angular distribution of the ω mesons in the c.m. frame of the colliding protons assuming the reaction goes through the $N^*(1900) \frac{3}{2}^+$ resonance. The experimental data from COSY-TOF [1] were obtained for an excess energy $\epsilon = 173$ MeV. The $p_{1/2}$ contribution $\sim 1 + 3 \cos^2 \theta_\omega^*$ 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.

ponent 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

$$\rho_{J_z J_z} = |C_{1/2 -J_z J_z}^{J0}|^2, \quad (3)$$

and so $\rho_{J_z J_z} = 1/2$ at $J_z = \pm 1/2$, and for a higher spin resonance, $\rho_{J_z J_z} = 0$ at $|J_z| \geq 3/2$. Equation (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.

The angular distribution of the ω mesons produced through the $N^*(1900)$ resonance decays can be found by weighting the polarization matrix (3) with the modulus squared of the $p\omega$ angular wave function (1) summed over the final-state $p\omega$ spin projections:

$$\frac{d\sigma}{d\Omega} \sim \sum_{J_z} \rho_{J_z J_z} \sum_{SS_z} \left| \sum_L A_{SL} C_{SS_z LL_z}^{JJ_z} Y_{LL_z}(\mathbf{n}_\omega) \right|^2. \quad (4)$$

The coefficient $C_{1/2 \mu_1 \mu_\omega}^{SS_z}$ entering the $p\omega$ wave function [cf. Eq. (1)] give a summation over the μ and μ_ω 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 πN multichannel partial-wave analysis and/or quark model predictions by Koniuk [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 [20] 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 the model [20] and experimental data [1]. This amplitude is shown in Fig. 1 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 ω -meson distribution. The distributions plotted in 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 $\Gamma_{N^*}^{\text{tot}}=500\pm 80$ [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 ω angular distribution compared to the $N^*(1900)$ decays at rest. To estimate this effect, let us compare velocities of the ω 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 ω 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 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 ω angular distribution. Let us check if $L=1$ and $L=2$ waves are allowed as 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 ${}^{2S+1}L_j^{2S+1}L_j$, 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

$$\frac{d\sigma}{d\Omega} \sim \sum_{S_z, L_z} |C_{S_z, L_z}^{j j_z} C_{S_z, L_z}^{j j_z} Y_{LL_z}(\mathbf{n}_\omega)|^2. \quad (5)$$

They are plotted on Fig. 2. Since in the resonance rest frame the ω meson is produced at rest, the ω momentum has in the pp c.m. frame in the same direction as the $N^*(1720)$ momentum. Thus, we have replaced in Eq. (5) \mathbf{n}_{N^*} with \mathbf{n}_ω .

The wave Nos. 6, 8, 3, and 2 with quantum numbers ${}^3f_2{}^3P_2$, ${}^3f_3{}^5P_3$, ${}^3p_2{}^3P_1$, and ${}^3p_1{}^3P_1$ 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. The resonance $N^*(1900)$ alone gives a stronger angular dependence, being in slightly better agreement with the data.

There exist four $L=2$ transition amplitudes: ${}^1d_2{}^3D_2$, ${}^1s_0{}^5D_0$, ${}^1d_2{}^5D_2$, and ${}^1g_4{}^5D_4$. The corresponding ω -meson an-

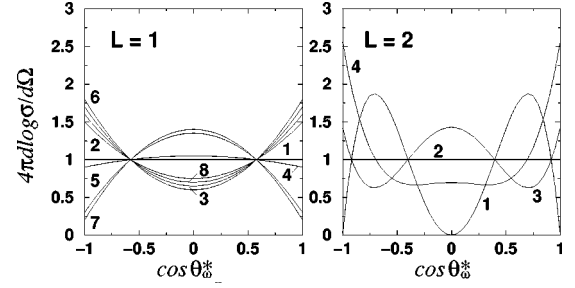


FIG. 2. Normalized $L=1$ and $L=2$ angular distributions of the $N^*(1720)_{\frac{3}{2}^+}$ resonance in transitions ${}^{2s+1}l_j^{2S+1}L_j$ where s , l , and j are the total spin, orbital momentum, and total angular momentum in the initial pp state. S and L are the total spin and orbital momentum in the final pN^* state. The numbers 1 to 8, attached to the $L=1$ curves, correspond to the waves ${}^3p_0{}^3P_0$, ${}^3p_1{}^3P_1$, ${}^3p_2{}^3P_1$, ${}^3p_1{}^5P_1$, ${}^3p_2{}^5P_2$, ${}^3f_2{}^3P_2$, ${}^3f_2{}^5P_2$, and ${}^3f_3{}^5P_3$, 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 ${}^1g_4{}^5D_4$.

gular 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 $\Gamma_{N^*}^{\text{tot}}=150\pm 50$ MeV [17]:

The off-shell $N^*(1720)$ production results in an ω distribution representing a convolution of the $N^*(1720)$ and ω angular distributions. As we estimated, at $m_{N^*}=1.76$ GeV the resonance and ω 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 in Fig. 2. The domain of 40 MeV above the ω threshold is not large compared to the resonance width. Hence, the pattern of the decay $N^*(1720)\rightarrow N\omega$ is important. According to Refs. [16,19] 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 ω couplings for the $N^*(1720)$.

The $N^*(1720)$ production cross section is parametrized as an S -wave process [11]. This resonance provides 10%–20% of the total $pp\omega$ cross section [13]. Such a value does not contradict the ω -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 meson production is set equal to zero [12–14]. In the region $\sqrt{s}\sim 2.8$ GeV the vector meson production, according to Refs. [12–14], is determined by tails of resonances of smaller masses and by the $N^*(1720)$. If we attribute the total cross section to the $N^*(1900)$ alone, we get $\sigma[pp\rightarrow pN^*(1900)]B[N^*(1900)\rightarrow p\omega]\sim 30\ \mu\text{b}$. Using

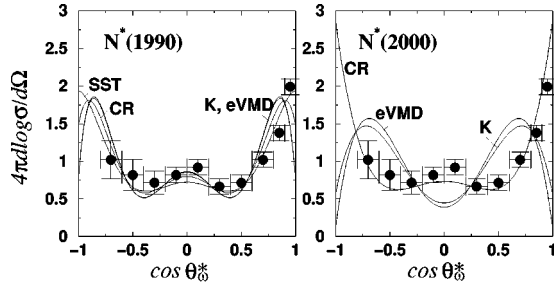


FIG. 3. Angular distribution of the ω mesons in the c.m. frame of the colliding protons assuming that the reaction proceeds through $N^*(1990)_{\frac{7}{2}^+}$ and $N^*(2000)_{\frac{5}{2}^+}$ decays. The models K [19], CR [20], SST [21], and eVMD [16] are compared to the DISTO data at $\sqrt{s} = 2.98$ GeV [2].

the estimate of Ref. [16] $\Gamma_{N^*p\omega} \sim 60$ MeV and the PDG value of $\Gamma_{N^*}^{\text{tot}} \sim 500$ MeV [17], 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 $v_\omega = 0$ 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 ω velocities at $\epsilon = 320$ MeV are equal to each other $v_\omega = v_{N^*} = 0.3$ at $m_{N^*} = 1.8$ GeV.

The approximation $v_\omega \sim 0$ 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 ω -meson data.

The approximation $v_{N^*} \sim 0$ is good for the resonances $N^*(1900)$, $N^*(1990)$, 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 $N^*(1990)$ and $N^*(2000)$ are shown in Fig. 3. The model [20] gives results close to the observations in both cases, the other models give reasonable angular dependences in the case of a $N^*(1990)$ dominance but stand in contradiction to a possible $N^*(2000)$ dominance.

The ϕ -meson angular distribution at $\sqrt{s} = 2.98$ GeV, i.e., 85 MeV above the ϕ -meson production threshold, is found to be consistent with an isotropic distribution [2]. The maximal ϕ momentum can be estimated in the c.m. frame to be $p_\phi^{\text{max}} = 0.33$ GeV and the maximal ϕ orbital momentum relative to the pp pair $\sim \eta_\phi = p_\phi^{\text{max}}/m_\pi = 2.4$. The S -wave ϕ -meson state allows $j^p = 1^-$ $pp\phi$ final states, whereas the higher orbital states are apparently excluded by the data, which is somewhat surprising.

The ω - ϕ mixing is sufficient to reproduce the ϕ -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 ϕ and ω mesons. To construct a 1^- final state out of the proton and a resonance in an S -wave, one needs negative-parity resonances. The well-established negative-parity resonances $N^*(1535)_{\frac{1}{2}^-}$, $N^*(1650)_{\frac{1}{2}^-}$, and $N^*(1700)_{\frac{3}{2}^-}$ with nonvanishing couplings to

ω mesons have low masses and can only contribute to the reaction through their Breit-Wigner tails. These resonances have dominant $s_{1/2}$ branchings [16,19] and thus their tails would produce an isotropic cross section. The resonances $N^*(2090)_{\frac{1}{2}^-}$ and $N^*(2080)_{\frac{3}{2}^-}$ 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 found to be

$$\rho_{J_z J_z} = \frac{2l+1}{2j+1} \sum_{s_z} |C_{ss_z 10}^{j s_z} C_{1/2 s_z - J_z J_z}^{j s_z}|^2. \quad (6)$$

For $s=0$, we recover Eq. (3). Equation (6) is valid for all $2s+1l_j$ states of two protons. The spin-half nucleon resonances are produced unpolarized. The diagonal elements of the $J = 3/2$ polarization matrix equal $\rho_{J_z J_z} = 1/8$ and $3/8$ for $J_z = \pm 1/2$ and $\pm 3/2$, respectively. So, the $N^*(2090)_{\frac{1}{2}^-}$ dominance in the $pp \rightarrow pp\phi$ or the dominance of any other spin-half nucleon resonance would result in a flat ϕ -meson distribution. The high-spin resonances are polarized and their dominance can apparently be excluded (except for $J = \frac{3}{2}^-$ resonances with the dominant $s_{1/2}$ decay modes).

Since the energy released in the process $pp \rightarrow pp\phi$ is small, it is instructive to compare the ϕ production with the near-threshold pion production which is well studied at $\epsilon_\pi \leq 20$ MeV [8]. The value of $\eta_\pi = p_\pi^{\text{max}}/m_\pi$ 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 Ref. [22]. With increasing η_π , 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 ω -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 Ref. [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 [23]. In the pp

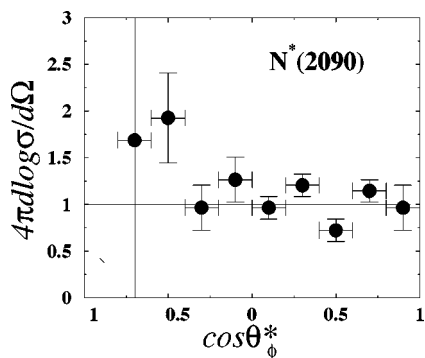


FIG. 4. Angular distribution of the ϕ mesons in the c.m. frame of the colliding protons measured by the DISTO collaboration at $\sqrt{s}=2.98$ GeV [2] is compared to the flat distribution (solid line) generated by the dominant $N^*(2090)\frac{1}{2}^-$ contribution in the reaction mechanism.

$\rightarrow pp\phi$ reaction, while the ϕ 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 Ref. [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 evidence for a strong dominance of the $N^*(2090)\frac{1}{2}^-$ or any other spin-half negative-parity resonance (see Fig. 4). We would otherwise expect on the pure kinematic grounds an isotropic angular distribution starting from the ω production threshold of $\sqrt{s}_\phi = 2.90$ 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 a first step in constructing a microscopic $NN \rightarrow NN^*$ transition potential using the t -channel exchange OBEP models or recently proposed an s -channel dibaryon exchange NN interaction model [24].

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 ω velocities in the N^* rest frames, which is a good approximation also for a significant off-shell spectral part of the $N^*(1720)$, the $N^* \rightarrow N\omega$ 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 ω production at $\sqrt{s}=2.83$ GeV. The several P and the one D wave of the $NN^*(1720)$ system generate also ω patterns close to the experimentally observed one.

At $\sqrt{s}=2.98$ GeV a dominance of $N^*(1990)\frac{7}{2}^+$ and 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 $\cos \theta_\omega^* \sim 0$. The $N^*(1720)$ generates the right pattern through the ${}^1g_4 {}^5D_4$ transition.

The ϕ -meson data can be explained by the dominance of the $N^*(2090)\frac{1}{2}^-$. It is not clear, however, why higher orbital states of the ϕ and, respectively, high-spin nucleon resonances which give anisotropic distributions, should not be involved in the ϕ -meson production.

We formulated also a general theorem according to which from every ${}^{2s+1}l_j$ initial state of two unpolarized protons, spin-half nucleon resonances are produced at 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 ω -meson production data while the ϕ -meson distribution cannot be interpreted so easily.

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