Study of ω- and ϕ-meson production in the reactions $\mathbf{pd \to dVp_{sp}}$ at ANKE

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Abstract

We propose to measure the cross section for pn $\to$ dω near threshold by studying the reaction pd $\to$ dωp$_{\rm sp}$ in deuterium in a region of quasi-free kinematics where the spectator proton has low momentum, typically 100 MeV/c. The deuteron will be measured in the forward detector of ANKE and the spectator proton by solid state counters placed in the reaction chamber in the backward hemisphere, thus allowing the ω to be identified as a missing-mass peak. A range of excitation energies can be covered by changing the beam energy or keeping it fixed and identifying Q on an event-by-event basis with the help of the spectator information. The modest energy resolution required and the expected cross section ($\sim 30 - 60\ \mu$b) at 2 GeV makes this an ideal early experiment for the ANKE facility.

Eventually we should like to extend such measurements to the production of the ϕ meson by selecting the K$^+$K$^-$ decay products in order to identify the meson and then carry out a kinematic reconstruction to evaluate the spectator momentum. The "experimental" amplitudes will be analysed within the two-step model which takes into account hadronic intermediate states for ω and ϕ production. Essential deviation of the measured ratio from the predictions of the two-step model might then provide information on the contribution of an intrinsic $\bar{\rm s}$s component in the nucleon wave function.

We plan to use an unpolarized proton beam of COSY and a cluster target for ω production while a pellet target with higher density will be necessary for ϕ production. Later, a polarized proton beam can be used for detecting the left-right asymmetry in ω and ϕ production as well as proton-ϕ spin-spin correlation, through the analysis of the angular distribution of kaons for up and down proton polarizations.

At a later stage we hope to determine the ωp elastic cross sections by selecting events with fast final protons that have received a recoil from the elastic scattering with the vector meson produced by the first nucleon. This would however require a clean identification of the ω from, for example, its $\pi^0\gamma$ decay using supplementary photon counters.

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1 Overview

Though great advances have been made in the measurement of meson production near threshold in proton-proton collisions, very few data points are available from the neutron-proton channel. In the case of η production, values of cross sections for $\mathrm{pn} \to \mathrm{d}\eta$ and $\mathrm{pn} \to \mathrm{pn}\eta$ have been deduced from quasi-free production from deuterium where, through kinematic reconstruction of the final particles, the values of the c.m. energy have been deduced on an event-by-event basis [1]. The Fermi motion inside the target has therefore been exploited in order to investigate the total cross section as a function of c.m. energy while keeping the beam energy fixed.

An alternative method of investigating the same reactions, but with a higher precision in c.m. energy, would involve measuring the momentum of the spectator proton directly. Since this is typically 50–100 MeV/c, such a proton would rarely be detectable with a standard external target. It is one of the great advantages of working with thin internal targets in circulating machines, such as CELSIUS or COSY, that low energy particles escape the target largely unscathed. This novel technique is currently being employed at CELSIUS to investigate the $\mathrm{pd} \to \mathrm{d}\eta\mathrm{p_{sp}}$ and $\mathrm{pd} \to \mathrm{pn}\eta\mathrm{p_{sp}}$ cross sections by measuring spectator protons in solid state counters placed inside the reaction chamber [2]. This method opens up the possibility of a new and exciting program for the measurement of a multitude of proton-neutron interactions at well-defined energies beyond the range of CELSIUS, with its limited energy and unpolarized beams. It is a program that the ANKE facility, with its large solid angle and flexibility in operation, is ideally suited to exploit.

It is the aim of the present proposal to show in detail how we can measure the $\mathrm{pn} \to \mathrm{d}\omega$ reaction using quasi-free production in deuterium and measuring the spectator proton in coincidence with the final deuteron in order to determine the ω as a missing-mass peak. In view of the width of the resonance, only modest resolution is required, which makes it a suitable early experiment for ANKE.

Though the spectator technique could be usefully extended also to the study of η and η' production, especially when good polarized beams and targets are available, we should also at some future date like to measure quasi-free ϕ production in $\mathrm{pn} \to \mathrm{d}\phi$. This is because of the intimate physics relationship between the production of the ω and ϕ vector mesons and the testing of the OZI rule. However, since the production cross section for ϕ mesons is significantly smaller and background conditions are worse, we suggest to in addition identify the reaction through the $\mathrm{K^+K^-}$ decay mode of the ϕ. Both the detection and the target would be different for the ϕ and we are not presently seeking approval for this part of the experiment but are outlining it in order to give a broad view of the physics involved with vector meson production.

Another direction in which we hope to extent the Physics program is through looking at $\mathrm{pd} \to \mathrm{d}\omega\mathrm{p_{sp}}$ at high spectator momenta. Provided that this reaction can be cleanly detected, then the tail of the Fermi momenta will be influenced by the rescattering of the ω meson from the spectator proton. This type of measurement thus opens up the possibility of investigating the scattering of unstable particles from nucleons. Just as in the case of the ϕ meson, this experiment is not for the near future because it would require cleaner identification of the ω meson. This would be achieved through detecting the 9% branching fraction of ω decays into $\pi^0\gamma$, using new supplementary photon detectors to be placed near the target. We also present arguments that by the measurement of high-momentum spectator protons in the reaction pn $\to$ dϕ it might be possible to give an upper limit for the ϕn elastic scattering cross section.

In summary, we request approval for an experiment to make a first measurement of the quasi-free production of ω mesons in proton-deuteron collisions by detecting the spectator protons. We further seek encouragement to continue the physics program by measuring ϕ production and also ω production away from the quasi-free region.

It should be noted that a natural extension of the studies described here is to measure the cross sections of η/η' production and the left-right asymmetry in all these reactions using a polarized proton beam. Using the polarized proton beam it will also be possible to measure the proton-ϕ spin-spin correlation looking for the angular distribution of kaons at different spin directions of the beam.

2 Physics case

The amplitudes for ω- and ϕ-meson production in proton-neutron reactions close to threshold so far are basically unknown — especially with a deuteron in the final state — and of interest in itself. Furthermore, it is well known (see e.g. [3–5]) that the ratio of the ϕ/ω yields

$$R = \frac{\sigma_{\mathrm{A+B}\to\phi\mathrm{X}}}{\sigma_{\mathrm{A+B}\to\omega\mathrm{X}}} , \tag{1}$$

where the initial and final hadrons do not contain strange quarks, is a particularly sensitive probe of the OZI rule [6] claiming that s$\bar{\mathrm{s}}$ production is suppressed substantially. With the deviation $\delta = \theta - \theta_{\mathrm{i}} = 3.7°$ from the ideal $\mathrm{SU}(3)_f$ mixing angle $\theta_{\mathrm{i}} = 35.3°$ we have $R/f = (4.2 \cdot 10^{-3})$ [5], where f is the ratio of the phase-space factors. However, experimental data show an apparent excess of R/f above the standard value which varies from $(10 - 30) \cdot 10^{-3}$ in πN and NN collisions to $(100 - 250) \cdot 10^{-3}$ in $\bar{\mathrm{N}}$N annihilation at rest and in flight (see e.g the discussion in [5]). In [5] the large excess of R in pp and $\bar{\mathrm{p}}$p collisions was explained in terms of "shake-out" and "rearrangement" of an intrinsic $\bar{\mathrm{s}}$s component in the nucleon wave function. On the other hand, in [7,8] the large excess in ϕ in $\bar{\mathrm{p}}$p annihilation at rest was explained in terms of hadronic intermediate K$\bar{\mathrm{K}}^*$ states which might create ϕ mesons.

Another argument in favour of large admixture of the hidden strangeness in nucleons is related to an apparently large contribution of the ϕ-meson into the isoscalar spectral function which through the dispersion relation defines the isoscalar nucleon form factor (see Ref.[9]). However as it was shown later on (see Ref.[10] and references therein) the main contribution to the isoscalar spectral function near 1 GeV comes from the correlated

$\pi\rho$ exchange which does not contain strange quarks.

Therefore, the large ratio R observed in $\bar{\rm p}$p annihilation at rest is unclarified. It is thus important to investigate hadronic processes where uncertainties in the interpretation of ω and ϕ production in terms of intermediate hadronic states are comparably small. A good choice in this respect is the reaction

$$\mathrm{pn} \to \mathrm{dV} \tag{2}$$

with $\mathrm{V} = \omega, \phi$. The measurements will be performed at beam energies $T_{\rm p} = 2.0$ (2.688) GeV in case of the ω (ϕ) meson, respectively. In comparison with earlier measurements, the advantages of the studies proposed here are as follows:

i) The ϕ-production studies will be performed at the maximum energy available at COSY corresponding to a momentum of the produced ϕ meson in the c.m. system of about 200 MeV/c. The ω production will be measured at a beam energy of 2.0 GeV which correspond to the same value of $p^{\rm cm}$. Thus, without any phase-space corrections one can directly determine the cross-section ratio R and the ratio of the S-wave amplitudes. Experiments on the ω and ϕ production in the reaction $\mathrm{pp} \to \mathrm{ppV}$ near the threshold were performed by the SPES3 and DISTO collaborations at SATURNE [11,12] (see also the calculations of ω production in [13]). The DISTO data were obtained at one energy $T_{\rm p} = 2.85$ GeV for both mesons i.e. at different $p^{\rm cm}$ for the ω/ϕ mesons. This complicates the determination of the ϕ/ω-amplitude ratio since phase-space corrections have to be applied. This makes it much harder to draw definite conclusions about the strangeness content of the nucleon. The authors stress that further measurements closer to threshold should be performed. Furthermore, near the threshold the dynamics of the reactions $\mathrm{pp} \to \mathrm{ppV}$, $\mathrm{pn} \to \mathrm{pnV}$ and $\mathrm{pn} \to \mathrm{dV}$) are different because the first one is constrained by Pauli principle and two protons in the final state should be in the $^1\mathrm{S}_0$ state. In the third case the final pn system is in the $^3\mathrm{S}_1$ state while in the second case it can be in both states. Therefore, a possible violation of the OZI rule is expected to be different in all three cases.

ii) The study of the reactions $\mathrm{pp} \to \mathrm{ppV}$ [13] and $\mathrm{pn} \to \mathrm{dV}$ [14] show that the one pion exchange plays a significant role in both cases. Therefore, one can expect that the vector-meson production in pn collisions will be considerably enhanced as compared to pp collisions.

iii) The deuteron in the final state is preferable as compared to the pn system due to a larger detection efficiency; since the maximal energy at COSY is only slightly above the threshold of ϕ-meson production the cross section of the reaction $\mathrm{pn(d)} \to \mathrm{d}\phi(\mathrm{p_{sp}})$ is significantly larger than the cross section of the reaction with proton and neutron in the final state, which is reduced by the 4-body phase space.

iv) Recent measurements of the ϕ/ω ratio in the reaction $\mathrm{pd} \to {}^3\mathrm{He}\ \mathrm{X}$ (performed at SATURNE II [15,16]) yield

$$R/f = \left(63 \pm 5\ {}^{+27}_{-8}\right) \cdot 10^{-3} \tag{3}$$

which is also clearly above the OZI expectation 4.2×10^{-3}. Our proposal has some similarity with the SATURNE experiment, but there are important differences: The dynamics of the reactions pn $\to$ dV and pd $\to^3$He X is different: in the former case we have realistic estimates of the background from hadronic intermediate states, while in the latter case the dynamics is not yet understood. According to [17] the two-step model underestimates the SATURNE data by a factor 2, while according to [18] the discrepancy of the two-step model with the data might be even larger when spin-effects are taken into account. Thus, it is expected that theoretical models for pn $\to$ dV should be more quantitative than for pd $\to^3$He X.

v) Within the framework of the line-reverse invariance (LRI) assumption the reaction pn $\to$ dV can be related to the Pontecorvo reaction $\bar{\mathrm{p}}$d $\to$ VN where the OBELIX collaboration has found a ϕ/ω ratio about $(321 \pm 74) \cdot 10^{-3}$ [19]. However, the two-step model predicts for this ratio in pn $\to$ dV reactions only about $(4-8)\cdot 10^{-3}$ [14]. If essential deviation from the prediction of the two-step model will be found, it might be considered as a signal of interesting physics and probably as a possible evidence for the "shake out" or "rearrangement" of an intrinsic $\bar{\mathrm{s}}\mathrm{s}$ component in the nucleon wave function.

Our second objective is to measure the elastic cross sections of ωp and ϕp interactions. Recently, an increasing interest in the study of vector-meson properties in hot and dense matter — as produced in heavy-ion collisions — has attracted much attention (cf. ref. [20] for a recent review on this topic). For example, a mass shift and an increase of the width of the ω meson with nuclear density is expected. However, both quantities (mass shift and collision broadening) depend (in first order) on the product of the nuclear density with the VN-scattering amplitude. Therefore, it is crucial to know the VN interaction cross sections experimentally. The reaction pn(d) $\to$ dV($\mathrm{p_{sp}}$) offers a good possibility to measure directly the ωp and ϕp elastic scattering cross sections. Here the deuteron plays the role both of the source of the vector mesons and also as a target for rescattering. Being produced near the threshold ω and ϕ have momenta of about 1 GeV/c in the lab. system and their mean-free path is larger than the average distance between the nucleons in a deuteron. Events with rescattering can be selected by choosing final protons with momenta essentially exceeding typical spectator momenta of $30-80$ MeV/c and looking for the back-to-back correlation between transverse momenta of the mesons and the recoiled proton.

3 Cross section estimates for ω and ϕ production

The total cross section for the production of ω mesons in the pp $\to$ ppω reaction has recently been measured near threshold at Saclay [11]. Analysis of this reaction within the framework of the meson-exchange model was done in ref. [13]. Phenomenologically, it is useful to describe the production cross section near the threshold in terms of a simple analytical function of the c.m. energy excess Q. Providing that the only strong final state interaction is that between the two protons, it is expected that the energy dependence should be of the form [21]

$$\sigma_T(\mathrm{pp} \to \mathrm{pp}\omega) = C\,F(Q) = C_\omega\,\epsilon\left(\frac{Q}{\epsilon}\right)^2\left(1+\sqrt{1+Q/\epsilon}\right)^{-2}\,, \tag{4}$$

where, including the Coulomb repulsion between the two protons, $\epsilon \approx 0.45$ MeV. After integrating over the ω width, the Saclay data are consistent with such a dependence with a value of $C_\omega = (100 \pm 20)$ nb/MeV.

The production of ω mesons in $\mathrm{pn} \to \mathrm{d}\omega$ is expected to be much stronger than in proton-proton collisions for two reasons. Firstly, if the production is dominated by isovector exchange, there is a favourable Clebsch-Gordan factor of 4.5 for the proton-neutron induced channels. This is well known for η production where it was found [22–24] experimentally that

$$\sigma_T(\mathrm{pn} \to \mathrm{pn}\eta)/\sigma_T(\mathrm{pp} \to \mathrm{pp}\eta) \approx 6.5 \pm 1.0\,. \tag{5}$$

Secondly, phase space favours the production of a bound deuteron in the final state, an effect which is largely independent of the nature of the produced meson [21].

We therefore estimate the required cross section by assuming that both the isospin effects and phase space factors are as for the η case, such that

$$\sigma_T(\mathrm{pn} \to \mathrm{d}\omega) \approx \sigma_T(\mathrm{pp} \to \mathrm{pp}\omega)\ \times\ \frac{\sigma_T(\mathrm{pn} \to \mathrm{d}\eta)}{\sigma_T(\mathrm{pp} \to \mathrm{pp}\eta)}\,. \tag{6}$$

Such a simple model predicts that

$$\sigma_T(\mathrm{pn} \to \mathrm{d}\omega) \approx D_\omega\sqrt{Q}\,, \tag{7}$$

where $D_\omega \approx 4.5\ \mu\mathrm{b/MeV}^{1/2}$. The cross section might be a little larger than this close to threshold because of the finite width of the meson [11].

The cross section has also been calculated in a microscopic one-pion-exchange model where the deuteron is formed *via* a neutron-proton final state interaction [14]. Neglecting the width effect, near threshold it is predicted that $D_\omega = 4.7 - 11.6\ \mu\mathrm{b/MeV}^{1/2}$, depending upon the range parameter in the form factor. These two types of calculations give very similar results and lead us to expect cross sections in the range 11–20 μb at $\mathrm{T_{lab}}$ = 1.9 GeV, increasing to 30–55 μb at 2.0 GeV. Values of this order also follow within the Rossendorf collision model [25], which predicts $\sim$ 50 μb at 2 GeV.

It is interesting to compare the cross section of the reaction $\mathrm{pn} \to \mathrm{d}\omega$ calculated in Ref.[14] with the cross section of the reaction $\mathrm{pp} \to \mathrm{pp}\omega$ analyzed within the framework of the meson-exchange model in Ref.[13]. This model predicts a cross section of about 2–3 μb at 2 GeV. It is by a factor 20 smaller than the cross section of the reaction $\mathrm{pn} \to \mathrm{d}\omega$ predicted in [14]. This is the consequence of the following factors: i) the dominance of the isovector meson exchange mechanism which gives approximately a factor 6 in favour of the pn $\to$ pnω cross section as compared to pp $\to$ ppω (as in the case of η production described by Eq.(5)) ; ii) the influence of the phase space near the threshold which suppresses the three-body final state as compared with the two-body state (see e.g.[21] and references therein); iii) the constructive interference of the forward and backward scattering amplitudes $A(s,t)$ and $A(s,u)$. Very near the threshold where the cross section is isotropic the interference of those amplitudes is complete it gives an enhancement factor of 4.

In a microscopic approach, as offered by the one-pion-exchange model, it is also possible to estimate ϕ production and this predicts [14] that this strength should lie in the range $D_\phi \approx 0.03 - 0.06$ μb/MeV$^{1/2}$, which is a factor of 200 less than for the ω. As it was demonstrated in [14], the one-pion exchange gives the dominant contribution to the cross section of the reactions pn $\to$ dω/ϕ near threshold. Thus the two-step model, based upon the dominance of the hadronic intermediate states, predicts a rather small ratio of the S-wave amplitudes for ϕ and ω production. The summary of the one-pion-predictions for the total cross sections for ω and ϕ production is given in Fig.1.

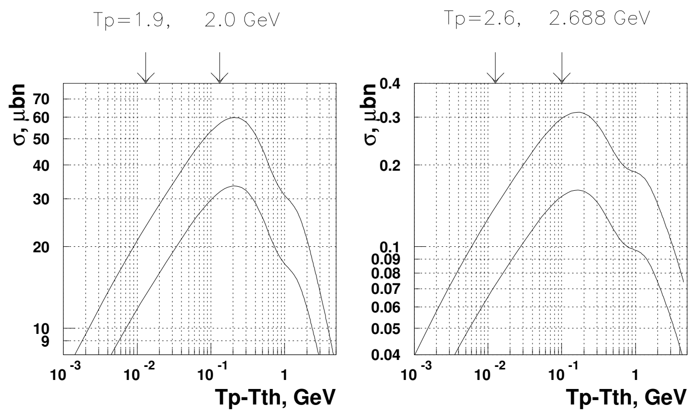

Fig. 1. Cross sections of the reactions pn $\to$ dω and pn $\to$ dϕ. The upper and lower curves are calculated with different values of the range parameter.

Away from threshold, the S-wave assumption is no longer valid and estimates are given in Fig.2 for the angular distributions of pn $\to$ dω at 2.0 and 2.6 GeV and pn $\to$ dϕ at 2.6 and 2.688 GeV within the framework of the quark-gluon string model developed by Kaidalov [26] and elaborated in Ref. [14].

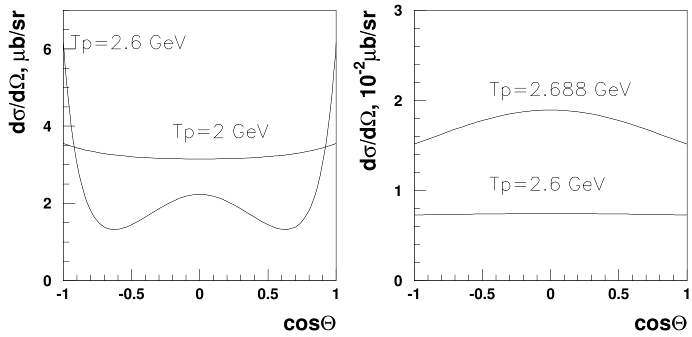

Fig. 2. Differential cross sections of the reactions pn $\to$ dω and pn $\to$ dϕ.

The angular distribution for ω production is almost isotropic at 2.0 GeV ($p_V^{cm} = 0.21$ GeV/c), which demonstrates the dominance of the S-wave. At 2.6 GeV, when many partial waves contribute, it is predicted to have very sharp forward and backward peaks. The angular distribution of ϕ production is completely isotropic at 2.6 GeV ($p_V^{cm} = 0.07$ GeV/c); it is predicted to become slightly anisotropic at 2.688 GeV with an excess of about 20% at 90° as compared to the forward and backward angles. It can be concluded from Fig.2 that in both reactions the S-wave dominates at $p_V^{cm} \simeq 0.2$ GeV/c.

4 Angular and momentum distributions of final particles in the reaction $\mathrm{pn(d)} \to \mathrm{d}\omega(\mathrm{p_{sp}})$ and main sources of background

Angular and momentum distributions of final deuterons and ω-mesons in the reaction $\mathrm{pn(d)} \to \mathrm{d}\omega(\mathrm{p_{sp}})$ are shown in Fig.3 by the solid (for 2.0 GeV) and dashed (for 2.6 GeV) histograms. The upper figures describe the momentum distributions. At 2.0 GeV the maximum of the momentum distribution is at 2.0 GeV/c for deuterons and near 0.9 GeV/c for ω mesons. At 2.6 GeV there are two maxima corresponding to the forward and backward peaks. In the case of forward deuterons the maximum is near 3 GeV/c for d and near 0.4 GeV/c for the ω. In the case of backward deuterons the maximum is near 1.5 GeV/c for d and near 1.9 GeV/c for the ω, respectively.

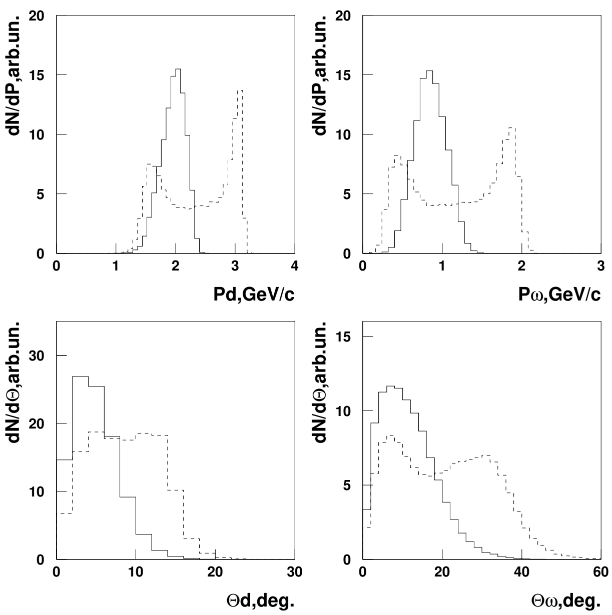

Fig. 3. Momentum (upper figures) and angular (lower figures) distributions of final deuterons and ω-mesons in the reaction $\mathrm{pn(d)} \to \mathrm{d}\omega(\mathrm{p_{sp}})$. Solid and dashed histograms correspond to the incident energy of protons 2.0 and 2.6 GeV, respectively.

The lower figures describe the angular distributions for deuterons (left) and ω mesons (right). For 2.0 GeV they are forward peaked at $\theta \leq 8°$ for d and $\theta \leq 16°$ for ω's. At 2.6 GeV deuterons and ω-mesons have broader angular distributions.

To select the reaction pn(d) $\to$ dω(p$_{\rm sp}$) we plan to measure the momentum and angle of the proton-spectator in coincidence with the fast forward deuteron and then gate on missing mass. At fixed incident proton momentum the missing mass depends on the momenta and angles of the final deuteron and proton spectator. The momentum distribution of proton spectators is presented in Sect. 6. It has the very well known form described by the deuteron wave function squared. The maximum of the spectator momentum distribution $\mathrm{d}N/\,\mathrm{d}p$ is near 60 MeV/c. For better detection efficiency we consider spectators with momenta $p_{\rm sp} \geq 50$ MeV/c and for best acceptance we consider the deuterons with $\theta_{\rm d} \leq 5°$. To make the best choice in the angular positions of the spectator detectors we present in Fig.4 the two-dimensional plot in the spectator angle $\theta_{\rm sp}$ versus deuteron momentum $p_{\rm d}$ (left). It is clearly seen that by selecting the deuterons with momenta around 2 GeV/c, the angular distribution of spectators with momenta $p_{\rm sp} \geq 50$ MeV/c has a maximum near $100 - 120°$.

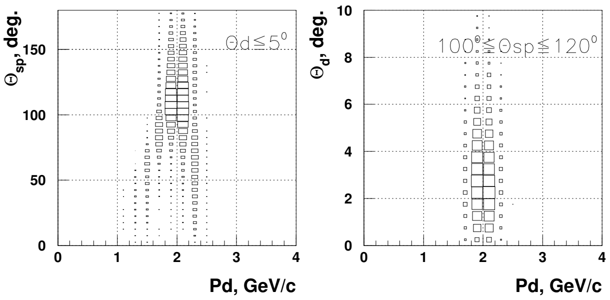

Fig. 4. Two-dimensional plots for the reaction pd $\to$ dωp$_{\rm sp}$ in the spectator angle $\theta_{\rm sp}$ versus deuteron momentum $p_{\rm d}$ (left) and in the deuteron angle $\theta_{\rm d}$ versus deuteron momentum $p_{\rm d}$ (right).

The two-dimensional plot in the deuteron angle $\theta_{\rm d}$ versus deuteron momentum $p_{\rm d}$ with the cuts in the spectator angle $100° \leq \theta_{\rm sp} \leq 120°$ and spectator momentum $p_{\rm sp} \geq 50$ MeV/c is shown in Fig.4 (right). The clear majority of the events are in a rather narrow interval of $p_{\rm d}$ around 2 GeV/c . The maximum of $\theta_{\rm d}$ distribution is between 1° and 5°.

For the same spectator cuts as in Fig.4 (right) we present in Fig.5 the two-dimensional plots in the deuteron angle $\theta_{\rm d}$ versus deuteron momentum $p_{\rm d}$ for two sources of the background: from the reactions pd $\to$ dρp$_{\rm sp}$ (left) and pd $\to$ dηp$_{\rm sp}$ (right). The cross section for the reaction pn $\to$ dρ was taken the same as for pn $\to$ dω. The background from ρ production gives a contribution to the same region as the ω, however, it is distributed over broader intervals in $\theta_{\rm d}$ and $p_{\rm d}$. Therefore, even for the same production cross section its contribution to the region $1.8 \leq p_{\rm d} \leq 2.2$ GeV/c, $\theta_{\rm d} \leq 5°$ is essentially smaller (see below). Associated η production has completely different kinematics and does not contribute to the region $1.8 \leq p_{\rm d} \leq 2.2$ GeV/c, $\theta_{\rm d} \leq 5°$.

Another source of background is related to the possible misidentification of protons and deuterons with the same momenta around 2 GeV/c. We present in Fig.6 the two-dimensional plot in the proton angle $\theta_{\rm p}$ versus proton momentum $p_{\rm p}$, calculated for the quasielastic pp-scattering pd $\to$ pnp$_{\rm sp}$ (left) and the reaction pd $\to$ pXp$_{\rm sp}$, where the

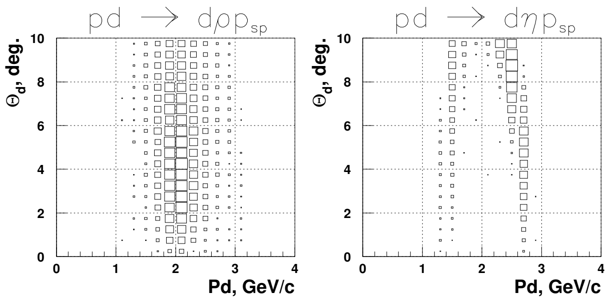

Fig. 5. The two-dimensional plots in the deuteron angle $\theta_{\rm sp}$ versus deuteron momentum $p_{\rm d}$ for the reactions pd $\to$ dρp$_{\rm sp}$ (left) and pd $\to$ dηp$_{\rm sp}$ (right).

hadronic system X contains nucleons and pions. The total cross section of this reaction is larger than the cross section of the reaction pn $\to$ dω almost by three orders of magnitude. However, events from this reaction populate a much broader region in the two-dimensional plot. If we make the cuts in spectator angle $100^\circ \leq \theta_{\rm sp} \leq 120^\circ$, spectator momentum $p_{\rm sp} \geq 50$ MeV/c as well as in deuteron angle $1^\circ \leq \theta_{\rm p} \leq 3^\circ$, we can find the double differential cross section as a function of the proton momentum for this reaction as presented by the dashed curve in Fig.7.

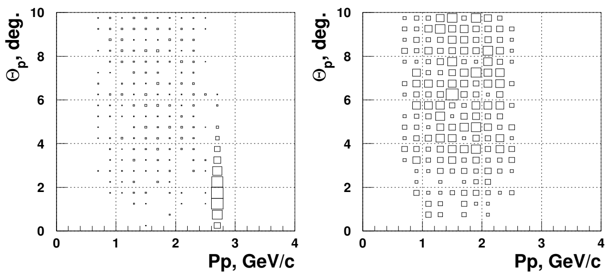

Fig. 6. Two-dimensional plot for the proton angle θ_p versus the proton momentum $p_{\rm p}$ for quasielastic pp-scattering (left) and the reaction pd $\to$ pXp$_{\rm sp}$ (right).

The dash-dotted and dotted curves in this figure show the double differential cross sections of ω and ρ production in the reaction pn $\to$ dV as a function of the deuteron momentum. The solid curve represents the sum of ω and ρ contributions. The total cross section of the reaction pn $\to$ dω was taken 60 μb. In the region of momenta $1.8 - 2.2$ GeV/c the ρ contribution is about 5 times smaller than the ω yield. The d/p ratio is about 0.5–1 if the ω production cross section is equal 30–60 μb.

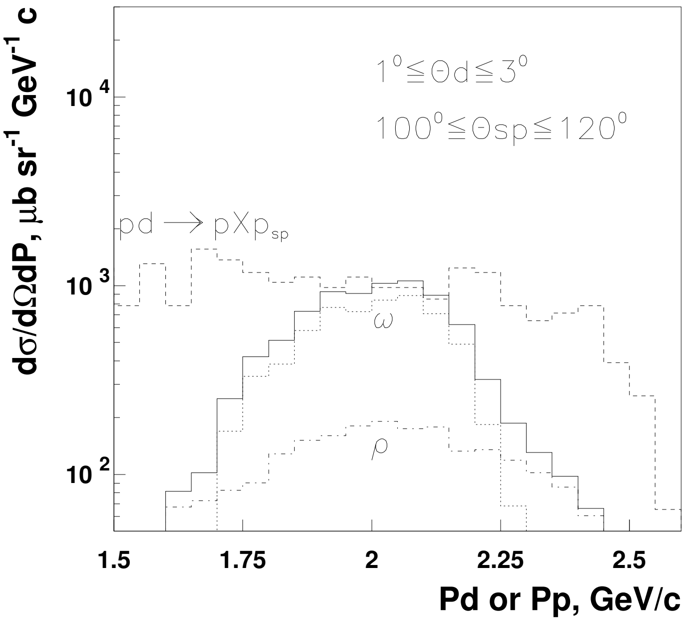

Fig. 7. Double differential cross sections for ω (dotted curve) and ρ (dash-dotted curve) production in the reaction $\mathrm{pn} \to \mathrm{dV}$ as a function of the deuteron momentum. The solid curve represents the sum of ω and ρ contributions. The background from the reaction $\mathrm{pd} \to \mathrm{pXp_{sp}}$ is shown by the dashed curve.

5 Angular and momentum distributions of final particles in the reaction $\mathrm{pn(d)} \to \mathrm{d}\phi(\to \mathrm{K^+K^-})(\mathrm{p_{sp}})$ and background

The momentum and angular distributions of final deuterons and ϕ-mesons are shown in Fig.8 at $T_\mathrm{p} = 2.668$ GeV. The maximum of the momentum distribution is near 2.2 GeV/c for deuterons and near 1.2 GeV/c for ϕ-mesons. The angular distribution has the maximum near 6° for deuterons and for ϕ-mesons. However, it is much broader for ϕ-mesons. Furthermore, the momentum and angular distributions of kaons from the decays of ϕ-mesons are shown in Fig.9. Here the maximum of the momentum distribution is near 0.6 GeV/c while the maximum of the angular distribution is near 9°.

We intend to identify the reaction $\mathrm{pn(d)} \to \mathrm{d}\phi(\to \mathrm{K^+K^-})(\mathrm{p_{sp}})$ by measuring the fast forward deuteron and $\mathrm{K^+, K^-}$ mesons. The background from the nonresonant $\mathrm{K\bar{K}}$ production can be estimated in a similar way as in case of $\mathrm{a_0}$ production [27].

6 Effects from ω and ϕ rescattering in the reactions $\mathrm{pd} \to \mathrm{d}\omega\mathrm{p}$ and $\mathrm{pd} \to \mathrm{d}\phi\mathrm{p}$

We now discuss our second objective: the measurement of the elastic $\omega\mathrm{p}$ and $\phi\mathrm{p}$ cross sections. In previous sections we have considered the cross sections of the reactions $\mathrm{pd} \to \mathrm{d}\omega\mathrm{p}$ and $\mathrm{pd} \to \mathrm{d}\phi\mathrm{p}$ within the framework of the spectator mechanism. This mechanism gives the dominant contribution to the cros section when the momentum of the proton-spectator is below 100–150 MeV/c. However, the produced meson can rescatter on a proton-spectator, thus transfering momenta larger than 200 MeV/c.

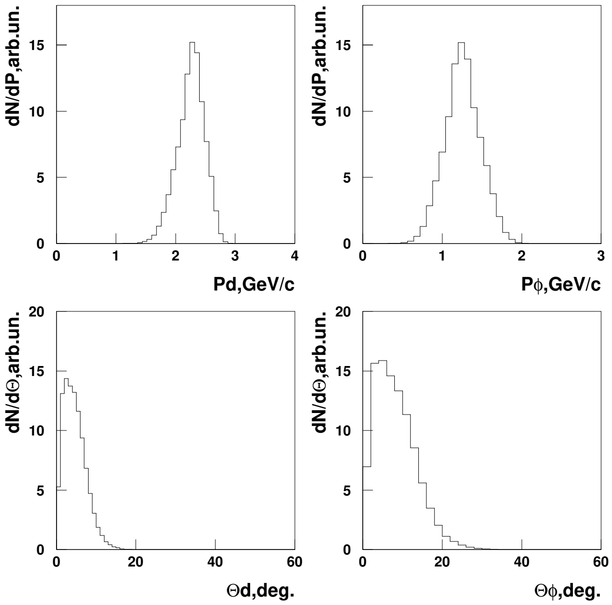

Fig. 8. Momentum and angular distributions of final deuterons and ϕ mesons in the reaction $\mathrm{pn(d)} \to \mathrm{d}\phi(\mathrm{p_{sp}})$ at $T_\mathrm{p} = 2.668$ GeV.

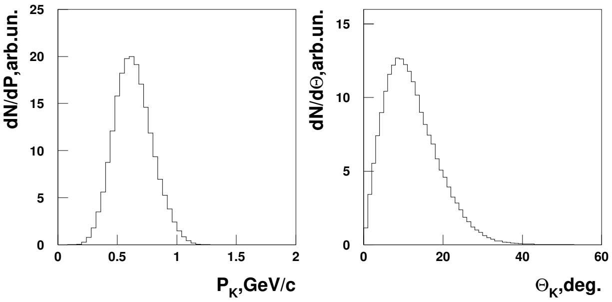

Fig. 9. Momentum and angular distributions of kaons in the reaction $\mathrm{pn(d)} \to \mathrm{d}\phi(\to \mathrm{K^+K^-})(\mathrm{p_{sp}})$ at 2.688 GeV

Experimentally proton-spectator spectra have been measured in $\bar{\mathrm{p}}\mathrm{d}$ annihilation [28,29]. In Fig.10 we present the momentum distribution of proton spectators in the reaction $\bar{\mathrm{p}}\mathrm{d} \to 3\pi^+2\pi^-\mathrm{p}$ at rest. The data are taken from [29]. The sharp peak with a maximum near 60 MeV/c corresponds to the spectator mechanism and the long tail above 200 MeV/c is due to rescattering of pions.

The effects of rescattering on the proton spectator in hadron-deuteron interactions have been discussed previously (see e.g. [30–33] and references therein). We note that the momentum distribution of the spectators can be written in the form

$$\frac{\mathrm{d}N(p)}{\mathrm{d}p} = p^2(|\psi_\mathrm{d}(p)|^2 + |\Psi_\mathrm{resc}(p)|^2)N, \tag{8}$$

where the first term is the contribution of the spectator mechanism with $\psi_{\rm d}(p)$ being the deuteron wave function in momentum space while N is the normalization factor. The second term $|\Psi_{\rm resc}(p)|^2$ appears due to rescattering of all the particles in the final state on the proton-spectator. The interference between the spectator and rescattering amplitudes is only important in a narrow region of spectator momenta, where both contributions are of the same order of magnitude (see, e.g. [31,32]).

The solid curve in Fig.10 is calculated using Eq. (8), where the deuteron wave function was taken in the parametrization of [34] with S- and D-waves included.

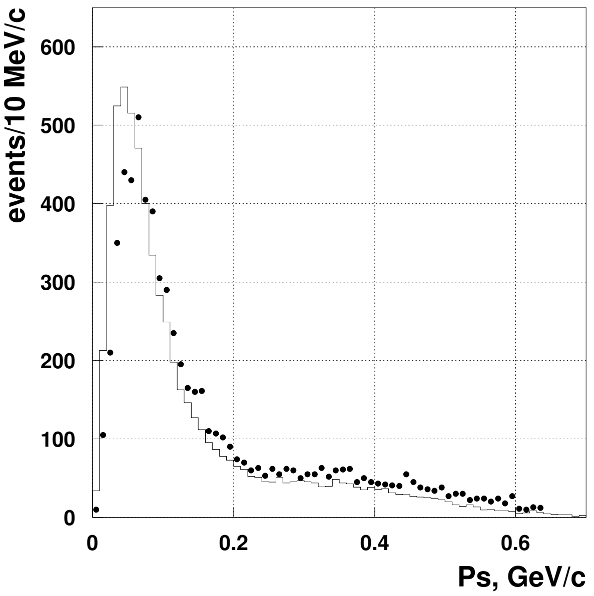

Fig. 10. Momentum distribution of proton-spectators in the reaction $\bar{\rm p}{\rm d} \rightarrow 3\pi^+2\pi^-{\rm p}$. The data are taken from [29]. The solid curve is calculated using Eq. (8)

The dependence of the second term on the momentum p in the lab. system is determined by the kinematical conditions (like the mass of the rescatterred particle) and by the angular dependence of the pion - nucleon scattering amplitude. In order to perform simulations of the momentum distributions, which are shown by the solid line in Fig.10, the Intranuclear Cascade Model (INC) [35] was modified:

i) The relative probability of pion rescattering was introduced in accordance with the multiple scattering theory (see e.g. [30]) :

$$\eta_j = \frac{\sigma_j \kappa^2}{2\pi^2}, \tag{9}$$

where

$$\kappa = \int {\rm d}r \phi_{\rm d}(r) \ . \tag{10}$$

ii) New parametrizations of the angular dependence of elastic and charge exchange πN cross sections were used.

The spectrum calculated by the INC model is in good agreement with the experimental data.

The same approach was used to simulate the momentum distributions of spectator protons in the reactions pd $\to$ dωp$_{\rm sp}$ and pd $\to$ dϕp$_{\rm sp}$. In Fig.11 we present three models for the angular distribution of ωN elastic rescattering (upper left) as well as the resulting spectator momentum distributions (upper right), where the most pronounced effect is seen for isotropic rescattering (solid histogram). The distributions in the azimuthal angle φ between the scattering planes show the most pronounced rescattering effects for fast spectators in line with the upper right part of the figure.

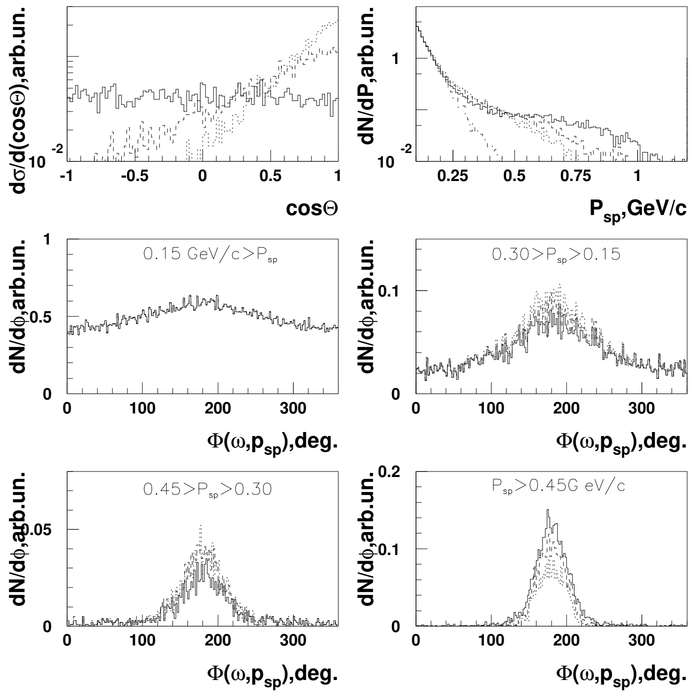

Fig. 11. Angular distribution of ωN elastic rescattering (upper left) within three different models. The resulting proton-spectator momentum distributions are shown in the upper right part for the three models in the reaction pd $\to$ dωp$_{\rm sp}$. In all calculations the ωN rescattering cross section $\sigma_{\rm el}$ = 40 mb was assumed. The distributions in the azimuthal angle φ between the scattering planes $\vec{p}_{\rm beam} - \vec{p}_\omega$ and $\vec{p}_{\rm beam} - \vec{p}_{\rm sp}$ for spectators with $p_{\rm sp} \leq 150$ MeV/c (middle left), 150 MeV/c $\leq p_{\rm sp} \leq$ 300 MeV/c (middle right), 300 MeV/c $\leq p_{\rm sp} \leq$ 450 MeV/c (lower left), and for fast spectators with $p_{\rm sp} \geq 450$ MeV/c (lower right) are shown additionally.

It is clearly seen that the spectator mechanism dominates at $p_{\rm sp} \leq 300$ MeV/c while at $p_{\rm sp} \geq 450$ MeV/c the main contribution stems from the rescattering term. The best way to select the rescattering term is to look for the correlation between the azimuthal angles of the two scattering planes $\vec{p}_{\rm beam} - \vec{p}_\omega$ and $\vec{p}_{\rm beam} - \vec{p}_{\rm sp}$ (lower figures). This correlation is much more pronounced for fast spectators ($p_{\rm sp} \geq 450$ MeV/c) than for slower ones ($p_{\rm sp} \leq 300$ MeV/c). It is worth to point out that the slope of the spectator spectrum depends on the slope of ωN angular distribution, while the correlation in the angle ϕ depends mainly on the value of the ωN elastic cross section.

Thus performing a cut for $p_{\rm sp} \geq 250$ MeV/c and $150^\circ < \varphi(\omega, p_{\rm sp}) < 210^\circ$ one can determine essentially the overall magnitude of the ωN elastic cross section (cf. upper part of Fig.12) whereas the number of events as a function of the cut in the proton-spectator momentum $p_{\rm sp}$ provides information on the ωN angular distribution. This is demonstrated in the lower part of Fig.12 for three models of the ωN angular distribution where the solid dashed and dotted lines correspond to the upper left part of Fig.11.

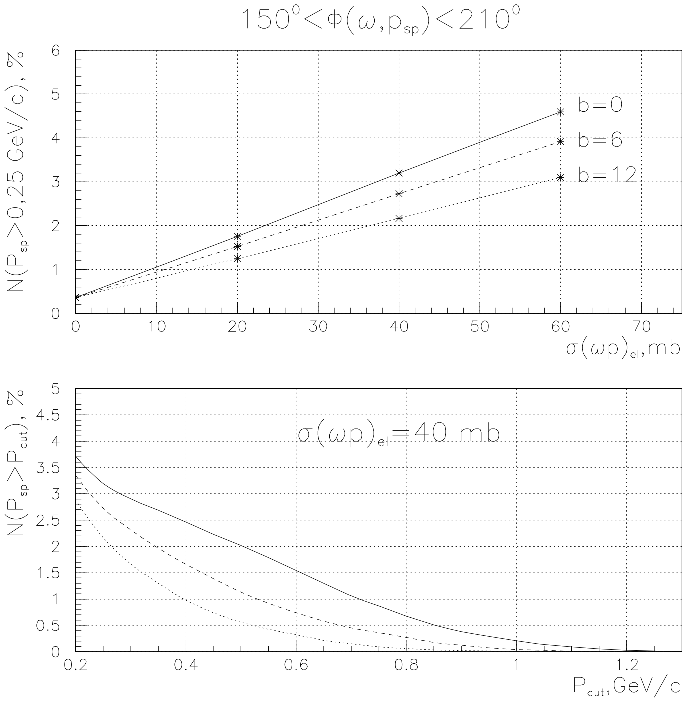

Fig. 12. Number of events for a cut for $p_{\rm sp} \geq 250$ MeV/c and $150° < \varphi(\omega, p_{\rm sp}) < 210°$ as a function of the elastic ωp cross section for three different angular distributions (solid, dashed and dotted lines) from the upper left part of Fig. 11 is displayed in the upper part. The lower part shows the number of events as a function of the cut in the proton-spectator momentum $p_{\rm sp}$ for the three different angular distributions assuming an overall magnitude of $\sigma(\omega \rm p)_{el} = 40$ mb in the reaction pd $\to$ dωp$_{\rm sp}$.

It is worth to point out that the relative contribution of the rescattering term is about few percent as compared to the spectator term. Therefore, the selection of the reaction pn(d) $\to$ dω(p$_{\rm sp}$) is more difficult because the relative contribution of the background related to the misidentification of protons with deuterons will be larger by two orders of magnitude. Moreover, the efficiency to detect fast protons is lower. Therefore, it will be important to identify the ω by measuring its decay products like $\pi^0\gamma$. The momentum and angular distributions of π^0 mesons and photons in the reaction pn(d) $\to$ d$\omega(\to \pi^0\gamma)$(p$_{\rm sp}$) at $T_{\rm p} = 2.0$ GeV are shown in Fig.13. The momentum spectra of pions and photons have maxima at 0.5 GeV/c. Thus the detection of such energetic photons will be a very good trigger for ω production, i.e. the selection of the reaction can be done by measuring the ω with a fast forward deuteron in coincidence.

In order to explore the possibility to measure the ϕN scattering amplitude we show in Fig.14 the momentum and angular distributions of proton-spectators in the reaction pd $\to$ dϕp$_{\rm sp}$.

The dotted curves correspond to the spectator mechanism. The solid and dashed curves are calculated with a ϕN rescattering term for $\sigma_{\rm el} = 15$ mb and different assumptions

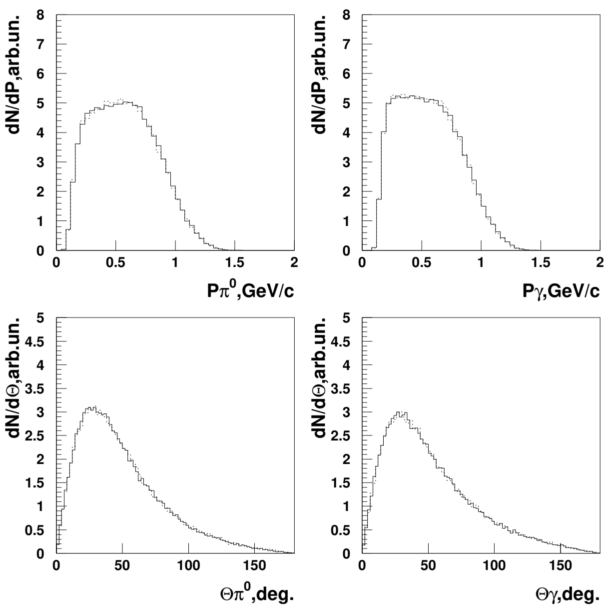

Fig. 13. Momentum and angular distributions of π^0 mesons and photons in the reaction $\mathrm{pn(d)} \to \mathrm{d}\omega(\to \pi^0\gamma)(\mathrm{p_{sp}})$ at $T_\mathrm{p} = 2$ GeV.

on the angular distributions: isotropic (dashed curve) and unisotropic as in the case of π^0N scattering (solid curve). The upper and lower figures have the same meaning as for the case of ω production (see Fig.11). Since the ϕN elastic scattering cross section is smaller than for ωN, the rescattering effect in this case is also smaller than in the case of ω production. Nevertheless, the effect of rescattering is seen in the tail of the spectator momentum distribution and in the correlation between the azimuthal angles of the two scattering planes $\vec{p}_\mathrm{beam} - \vec{p}_\phi$ and $\vec{p}_\mathrm{beam} - \vec{p}_\mathrm{sp}$ for fast spectators ($p_\mathrm{sp} \geq 200$ MeV/c) (lower right figure). As the rescattering effect becomes most noticeable at recoil momenta larger than 450 MeV/c, where the magnitude of the cross section is rather small, it might be questionable to distuinguish different angular distributions. However, the measurement of the correlation might yield useful information on the integrated elastic ϕN scattering cross section. Due to the apparently small cross section we apply for no dedicated beam time to measure the ϕN scattering, however, from the proposed measurement of the ϕ production cross section (see Sect.8.3) one can hope to obtain as a by-product at least an upper limit for its value.

7 Experimental program

As a consequence of the theoretical considerations presented in Sections 3–6 the following experimental program is suggested:

- Determination of the ω-production cross section in pn collisions by measuring the reaction $\mathrm{pd} \to \mathrm{d}\omega\mathrm{p_{sp}}$ at $T_\mathrm{p} = 2.0$ GeV.
- Measurement of p^cm and angular dependence of the ω-production cross section at beam energies around $T_\mathrm{p} = 2.0$ GeV.

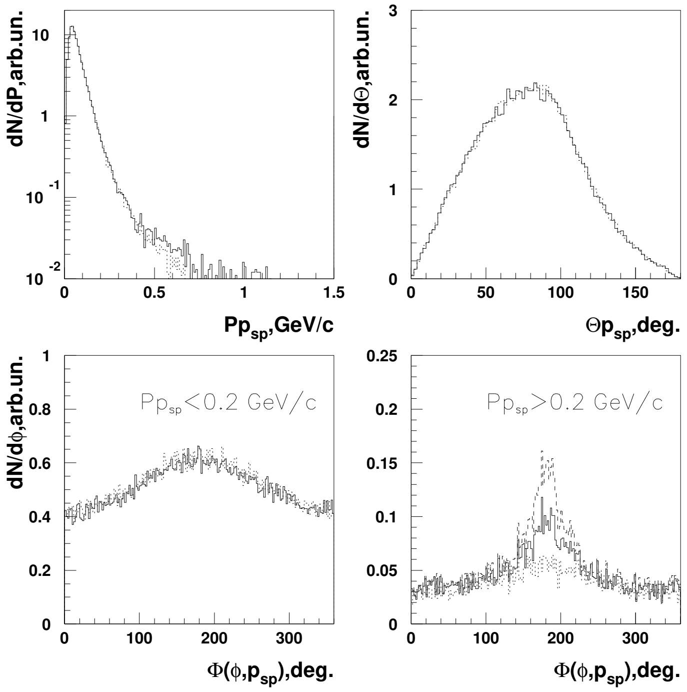

Fig. 14. Momentum and angular distributions of proton spectators in the reaction $pd \to d\phi p_{sp}$. The dotted curves correspond to the spectator mechanism. The solid and dashed curves were calculated with a ϕN rescattering term taking $\sigma_{el} = 15$ mb and different assumptions for the angular distributions: isotropic (dashed curve) and unisotropic as in the case of $\pi^0 N$ - scattering (solid curve).

- Determination of the ϕ-production cross section in pn collisions by measuring the reaction $pd \to d\phi p_{sp}$ at the maximum available COSY energy.
- Determination of the ωp-scattering cross section by measuring fast spectator protons from the reaction $pd \to d\omega p$ at $T_p = 2.0$ GeV.

In Sect.8 the experimental setups for the various measurements are presented as well as estimates for the counting rates and possible background. All simulation calculations were performed using the GEANT program package and taking into account the measured field distributions in the spectrometer magnet D2. Some of the results on the experimental conditions are summarized in the following table.

Reaction	T_{beam} [GeV]	Target	Spectator counter	Neutral particle detector
$pd \to d\omega p_{sp}$	2.0	cluster	prototype	no
$pd \to d\omega p_{sp}$	1.9–2.1	cluster	high acceptance	no
$pd \to d\phi p_{sp}$	T_{max}^{COSY}	pellet	high acceptance	no
$pd \to d\omega p$	2.0	pellet	high acceptance	yes

8 Experimental set-up

8.1 Description of the apparatus

The ANKE spectrometer [36] (see Fig.15) will allow to measure simultaneously positively and negatively charged particles emitted at small angles $\leq 10°$ with momenta larger than 150 MeV/c. Close to the target there is sufficient space for the installation of counters for spectator protons and also for neutral particles.

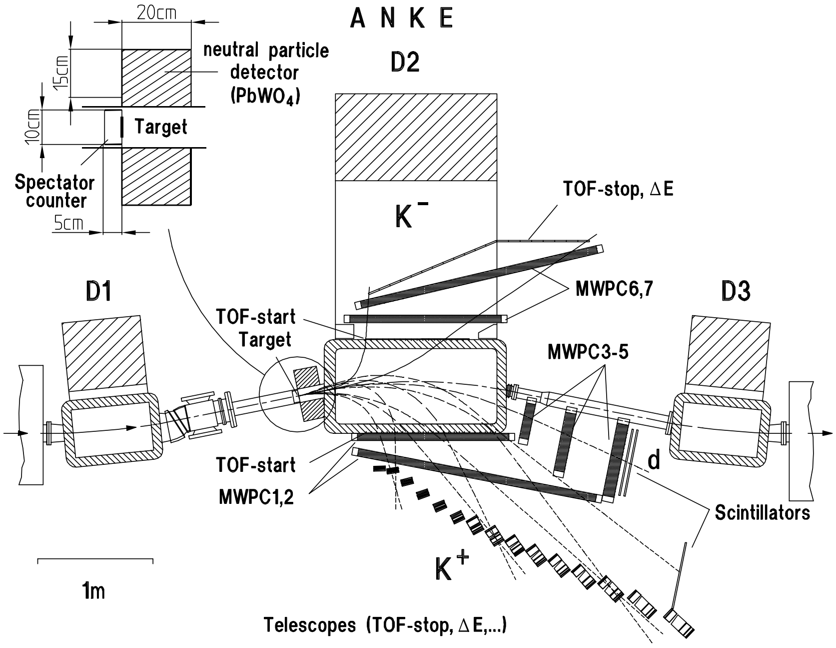

Fig. 15. Layout of the setup at the ANKE spectrometer. Also indicated are (not yet existing) counters for spectator protons with large acceptance and for neutral particles.

It is foreseen to use different targets at ANKE: in the early stage of the experimental program (first half of 1999) a cluster target built by the University of Münster will be used. It offers luminosities of up to $L \approx 10^{31}$ cm^{-2} s^{-1}. Approximately one year later, the frozen-pellet target [27] will be available. It will allow to measure small cross sections with good statistical accuracy since luminosities of up to $L \approx 10^{33}$ cm^{-2} s^{-1} can be reached.

The forward detector, which is located between D2 and D3, will detect positively charged particles with momenta between 1.0 and 3.2 GeV/c [37]. According to the calculations presented above, the deuterons from the reactions pd $\rightarrow$ dωp$_{\rm sp}$ and pd $\rightarrow$ dϕp$_{\rm sp}$ have momenta of about 2.0 GeV/c and are emitted into a narrow forward cone. Thus, they can be detected in the ANKE forward detector. The deuterons can be discriminated against protons and other background particles by TOF and ΔE measurements. The momentum resolution for the deuterons is $\Delta p/p \approx 1$ % yielding a good missing-mass resolution for the produced meson (see below).

The K$^+$ mesons will be detected in the side detection system [38,39] which will offer a K$^+$-detection efficiency of $\sim 10\%$ (including decay-in-flight between detectors and target) and a background supression (pions, protons and ejectiles scattered at the magnet iron) of more than 5 orders of magnitude [39–43] in the momentum range between 150 and 600 MeV/c. Thus, it allows to select events where a K^+ meson is produced with almost no background from other reaction channels.

K^- mesons can be detected in detectors which will be located in the window of the return yoke of D2 [44]. By measuring in coincidence with the K^+ telescopes they will allow to select reaction channels where K^+K^- pairs are produced with almost no background from other reactions. Thus, from an invariant-mass analysis one can select those events where a ϕ mesons is procuced with a mass resolution better than $\Delta m_\phi \approx 5$ MeV/c^2 [45]. The K^- detectors will be installed in the year 2000.

The spectator protons can be detected in a three-layer Silicon detector with an active size of 300 mm^2 and thicknesses of 18.5 μm, 300 μm and 4.5 mm. The counters are located in a distance of 12 cm to the target corresponding to a solid angle of $\sim$ 1.7 msr. An angular resulution of better than 0.5° can be achieved. The orientation relative to the target can be adjusted according to the experimental requirements. They have already been tested at ANKE. It is planned to build a spectator counter which covers a much larger solid angle. This counter could be used for the measurement of ϕ production where the involved cross sections are small.

For the detection of neutral particles it is planned to build a detection system close to the target region which covers the forward angular region. These detectors could e.g. be made from $PbWO_4$ which recently became well known as a fast, dense and highly radiation resistant material [46]. Since the geometry of the setup has not been fixed yet, we use for our simulations a very simple setup which has the shape of a hollow cylinder.

8.2 Detection of ω mesons

Since in the case of ω production in pd collisions the involved cross section is rather large ($\sigma \approx 60\ \mu$b) this reaction can be studied using the cluster-jet target with lower density and the small (already existing) counter for the detection of the spectator protons. Certainly, a dedicated spectator counter with larger angular acceptance will be needed for systematic measurements of the ω production, in particular for measurements close to threshold. In this section we show, however, that even with the small counters first results can be obtained and valuable information for the design of the more sophisticated system can be expected.

According to the angular distributions presented in Sect.4 most of the spectator protons from ω production are emitted into angles $\vartheta_{\mathrm{sp}} \approx 100 \ldots 120°$. The counter was, therefore, positioned at $\vartheta_{\mathrm{sp}} = 108°$. In the simulation ejectiles stemming from the reaction $\mathrm{pd} \to \mathrm{d}\omega\mathrm{p_{sp}}$ with momenta calculated according to Sect.4 were started at the target and traced through the spectrometer and the detectors. In order to estimate the background conditions also ejectiles from the reactions $\mathrm{pd} \to \mathrm{d}\rho\mathrm{p_{sp}}$ and $\mathrm{pd} \to \mathrm{pXp_{sp}}$ were simulated. It has already be shown in Sect.4 that under the kinematical conditions considered here deuterons from ρ production are almost by one order of magnitude less frequent than from ω production and that even without any proton/deuteron discrimination one expects a signal from ω production above the proton background — cf. Fig.7. Thus, only a moderate proton rejection has to be achieved with the forward counters in order to select the reaction with a deuteron and an ω meson in the exit channel.

The upper spectrum in Fig.16 shows the simulated energy loss of the protons in the first two layers of the spectator counters. The slow spectator protons can be identified against background from fast protons and pions by setting an appropriate gate on large energy losses. The lower spectrum in Fig.16 shows the energy loss in the forward scintillators vs. the time difference between the detection of the spectator proton and the forward going particle. The background protons are clearly separated from deuterons stemming from ω and ρ decay.

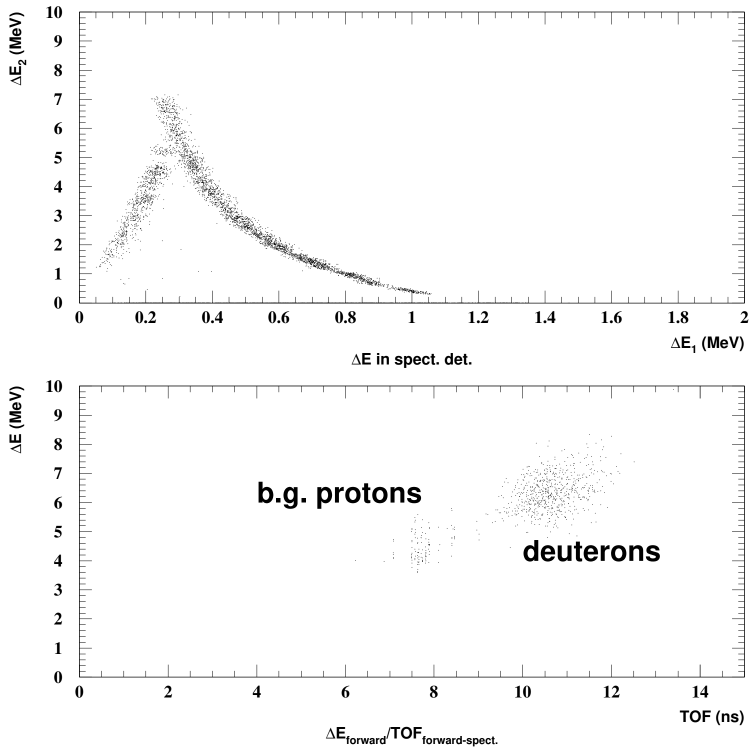

Fig. 16. Simulated energy-loss spectrum (upper) of spectator protons in the first two layers of the spectator counter. The lower spectrum shows the time difference between the detection in the forward scintillator and the spectator counter.

Figure 17 shows the momentum and angular spectra of deuterons and background protons detected in the forward counter in coincidence with the spectator proton. The ejectile-momentum vectors were calculated from the wire-chamber information using a fast matrix method [47] which will also be used for the analysis of experimental data at ANKE. According to previous calculations (see e.g.[27]) a momentum resolution of $\Delta p/p \approx 1\%$ can be achieved.

In Fig.18 we show the momentum spectra of the ejectiles detected in the forward counter after applying appropriate gates in the spectra of Figs.16 and 17. It can clearly be seen

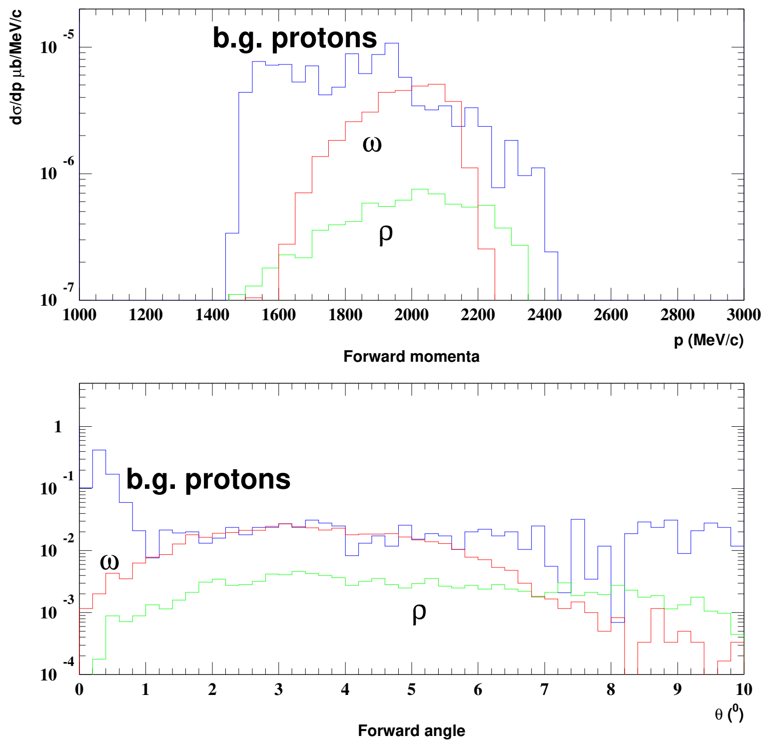

Fig. 17. Momentum (upper) and angular (lower) spectra of deuterons and background protons in the forward counters.

that all the background protons are suppressed and there are only few remaining events from ρ production. The lower spectrum in Fig.18 shows the mass distribution of the ω meson calculated from the 4-momenta $\mathcal{P}_{\rm d}$, $\mathcal{P}_0$, $\mathcal{P}_{\rm n}$ of the deuteron, the beam proton and the target neutron according to the formula

$$m^2(\omega) = \mathcal{P}_\omega^2 = (\mathcal{P}_0 + \mathcal{P}_{\rm n} - \mathcal{P}_{\rm d})^2 \approx (T_0 + T_{\rm n} - T_{\rm d})^2 - (\vec{p}_0 + \vec{p}_{\rm n} - \vec{p}_{\rm d})^2 \ . \qquad (11)$$

For the calculation it was assumed that the beam energy (momentum) T_0 ($\vec{p}_0$) is known precisely; the deuteron momentum $\vec{p}_{\rm d}$ has an uncertainty of $\sim 1\%$, see above. The neutron momentum can be taken as

$$\vec{p}_{\rm n} = -\vec{p}_{\rm sp} = 60 \cdot (\sin(\vartheta), 0, \cos(\vartheta)) \ \ {\rm MeV/c} \qquad (12)$$

assuming an angular resolution of $\delta\vartheta \approx 0.5°$ and that the spectators have a fixed momentum of $p_{\rm sp} = 60$ MeV/c (approximately maximum in the momentum distribution of the spectators). It should be noted that, in principle, the spectator momentum could be deduced from the energy losses in the counter (Fig.16) but even with the simplified approach chosen here, a missing-mass resolution for the ω of $m(\omega) \approx 10$ MeV/c^2 can be achieved.

According to our simulation calculation the geometrical acceptance at ANKE for the detection of spectator protons and deuterons from ω production is $A_\omega({\rm dp_{sp}}) \approx 0.08\%$.

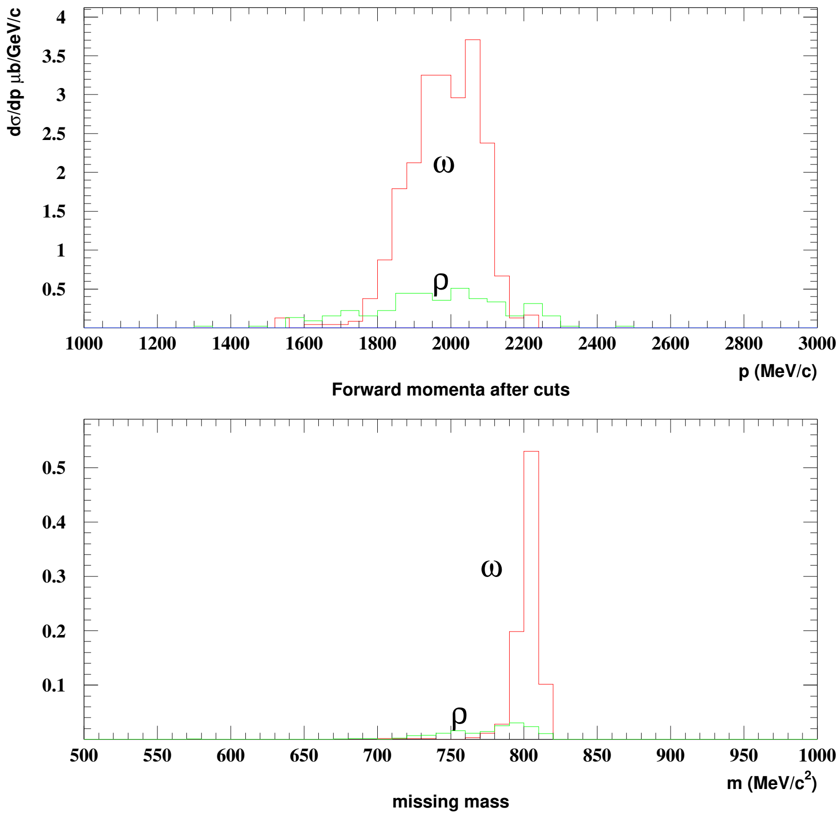

Fig. 18. Momentum spectrum (upper) of the remaining ejectiles detected in the forward hodoscope after applying appropriate gates in the TOF and ΔE spectra shown in Fig.16. The calculated missing mass of the spectator protons and the deuterons is shown in the lower figure.

Assuming a luminosity of $L \approx 10^{31}$ cm^{-2} s^{-1}, a detection efficiency of $\varepsilon \approx 50\%$ we expect a counting rate of

$$\dot{n} = L \cdot \sigma \cdot A_\omega(\mathrm{dp_{sp}}) \cdot \varepsilon \approx 15 \text{ min}^{-1} \ . \tag{13}$$

for an ω-production cross section of 60 μb.

From our simulations we expect a total proton rate in the spectator counter of ~ 500 s^{-1} which can easily be detected and processed by the DAQ electronics.

We conclude that ANKE is well suited for the detection of ω mesons from pd collisions even with the simple existing setup presented here. Thus, the measurements can be performed in an early stage of the experimental program at ANKE as soon as the cluster target will be installed. A few days of beam time should be sufficient to collect data with high statistical accuracy.

Systematical studies will be performed later using a high acceptance spectator counter. As an example, Fig.19 shows the ω-production cross section as a function of p^{cm}, i.e. the ω momentum in the c.m. system. Again, in the simulation we used the already existing setup with low angular acceptance and the cross sections calculated in section 3. It can be seen that by a variation of the beam energy, the p_{cm} dependence can be determined even with the low acceptance setup. The spectra shown in the figure correspond to a few hours of beam time.

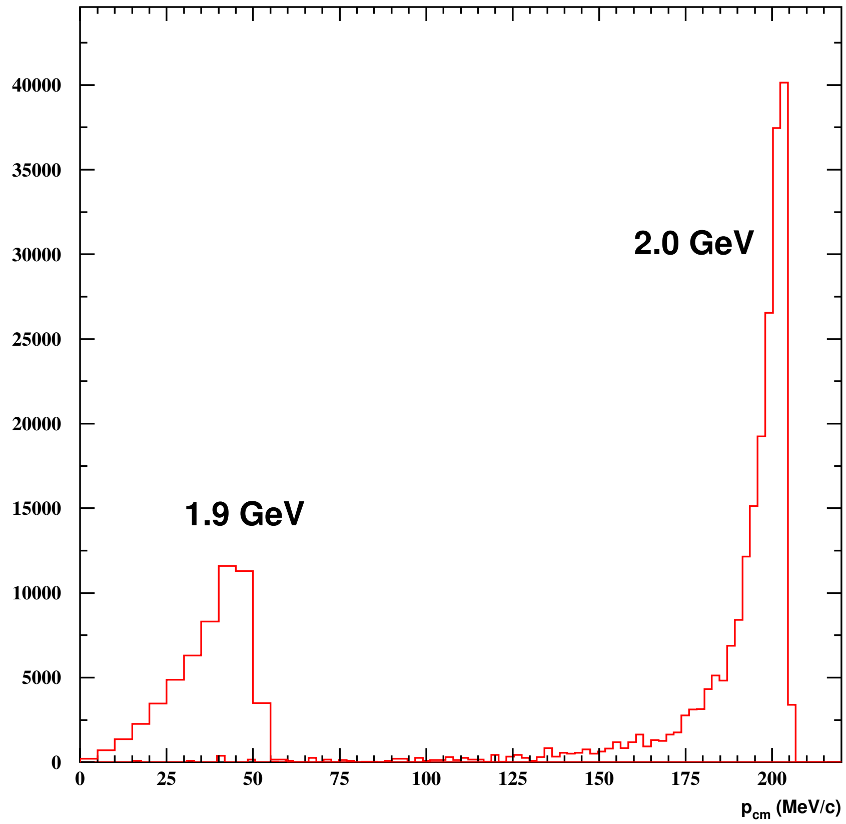

Fig. 19. Reconstructed cm-momentum spectrum for the ω meson.

8.3 Detection of ϕ mesons

In the case of ϕ production the involved cross sections are approximately two orders of magnitude smaller than in the case of the ω. It will, therefore, be neccessary to use a target with higher density and a spectator counter with higher angular acceptance. For the simulations presented in this section we assume a spectator detector which has the shape of a hollow cylinder with a diameter of 10 cm and a length of 5 cm covering an angular range of $\vartheta = 90° \ldots 135°$, see Fig.15.

The ϕ meson can be identified at ANKE via its decay into K^+K^- pairs which can be detected in coincidence. The acceptance of ANKE for the detection of the kaons (c.f. Fig.9) is about 1%, the missing-mass resolution for the ϕ meson is better than $\Delta m_\phi \approx 5$ MeV/c^2 [45]. Note, that this mass resolution is independent of the angular and momentum resolution of the spectator counter since the ϕ mass is reconstructed from the momenta of the two kaons. As shown in Sect.5 the background of non-resonant K^+K^- pairs is expected to be very small. Thus, at ANKE the reaction $pd \to d\phi p_{sp}$ can be identified almost free of background by measuring in coincidence all four particles in the exit channel (see also [44]).

According to our simulation calculation the geometrical acceptance at ANKE (with the high-acceptance spectator counter) for the detection of spectator protons, deuterons and the K^+K^- pair (including decay in flight) from ϕ production is $A_\phi(K^+K^-dp_{sp}) \approx 0.3\%$. Assuming a luminosity of $L \approx 10^{32}$ cm^{-2} s^{-1} (pellet target), a detection efficiency of $\varepsilon = \varepsilon_{sp}\varepsilon_d\varepsilon_{K^+}\varepsilon_{K^-} \approx 0.9 \cdot 0.9 \cdot 0.5 \cdot 0.9 \approx 0.36$ we expect a counting rate of

$$\dot{n} = L \cdot \sigma \cdot A_\omega(K^+K^-dp_{sp}) \cdot \varepsilon \approx 300 \text{ h}^{-1} , \tag{14}$$

for a ϕ-production cross section of 700 nb.

We conclude that ANKE is also well suited for the detection of ϕ mesons from pd collisions if one uses the high density frozen-pellet target and a new large acceptance counter for the detection of spectator protons. One week of beam time should be sufficient to collect data with high statistical accuracy. The measurements can be performed as soon as the pellet target will be available (beginning of 2000) and a new Silicon spectator counter has been developed.

8.4 Measurement of the ω-spectator rescattering

For the measurement of ωp rescattering it is neccessary to i) identify the reaction pd $\rightarrow$ dωp$_{sp}$ and ii) to measure the fast ($p_{sp} > 300$ MeV/c, see Fig.11) rescattered spectator proton. Do to the higher momenta of the scattered protons their energy-loss signal in the spectator counter will be significantly smaller than for unscattered ones (Fig.16). It will, therefore, be much harder to identify these protons and to discriminate them agains background particles, and, consequently it is desirable to *directly* identify the ω meson by measuring its decay $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ (B.R. 8.5%). The development of a detector for neutral particles for ANKE has begun. It could consist of $PbWO_4$, a fast and compact scintillator material with a radiation length of only 9.38 mm [46]. For the simulation we have assumed a detector in the shape of a hollow cylinder with an inner diameter of 12 cm a thickness of 15 cm and a length of 20 cm. It covers an angular range of $\vartheta_\gamma \approx 20° \ldots 90°$, see Fig.15. It could be combined with the high acceptance spectator counter presented in the previous section. The detection of the deuterons would be analogous to Sect.8.2.

In the simulation, the ejectiles (deuteron, spectator proton, three γ's) with momenta according to Fig.13 were started at the target and traced to the detectors. Figure 20 shows the energy deposited in the shower detector. Most of the events ($\sim$ 58%) lie in the peak around 1100 MeV which stems from the detection of all three decay γ's. Some background ($\sim$ 39%) from the detection of only one or two γ's at lower energies is visible. Only in very few cases ($\sim$ 3%) no γ is detected. One can therefore efficiently use an energy loss in the shower detector indicated by the shaded area in Fig.20 to select reactions where an ω meson has been produced. The ω mass can then be reconstructed from the momenta of the deuteron and the spectator proton as in Sect.8.2 with an accuracy of better than 40 MeV/c^2.

Figure 21 shows the momentum of the rescattered spectator protons p_{sp} calculated from

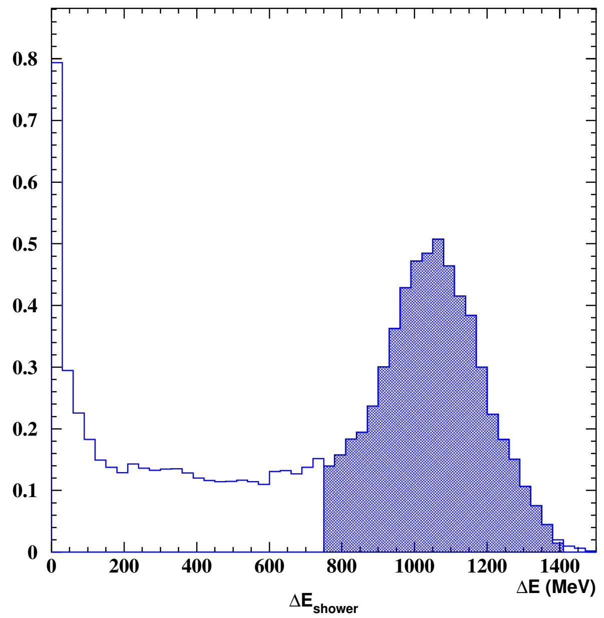

Fig. 20. Energy loss of the γ's from ω decay in the shower detector. The shaded area indicates the case when all three γ's from ω decay are detected.

the measured energy loss in the spectator counter ΔE according to the formula

$$p_{\rm sp} = \sqrt{\left[\left(\frac{\Delta E}{1.03}\right)^{1.20} + m\right]^2 - m^2} \tag{15}$$

which was deduced from energy-loss tables.

Figure 22 shows the angular correlation of the spectator protons from Fig.21 with the ω mesons. The spectator-emission angle can be measured directly with the spectator counter with high accuracy whereas the ω momentum $\vec{p}_\omega$ can be reconstructed from $\vec{p}_{\rm sp}$ (Fig.21) and $\vec{p}_{\rm d}$: $\vec{p}_{\rm sp} = \vec{p}_0 - \vec{p}_{\rm sp} - \vec{p}_{\rm d}$. In principle, $\vec{p}_\omega$ can also be reconstructed from the energy deposited in the shower counter. Since this would require a rather complicated data-analysis procedure this method is not applied here. It can be seen from Fig.22 that the strong correlation shown in Fig.11 is preserved in the "measured" data. We, therefore, conclude that ANKE should be well suited for the measurement of the ω-spectator rescattering.

It should be noted that the direct identification of the ω-meson would also allow to measure the cross section of the reaction $\rm pd \to pn\omega p_{sp}$ by detecting in addition the fast proton and the slow proton spectator.

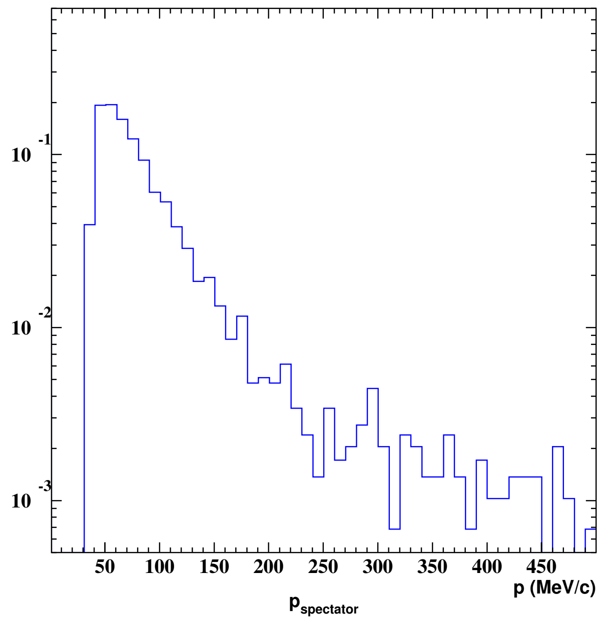

Fig. 21. Momentum of the rescattered spectator protons calculated from the measured energy loss in the spectator counter.

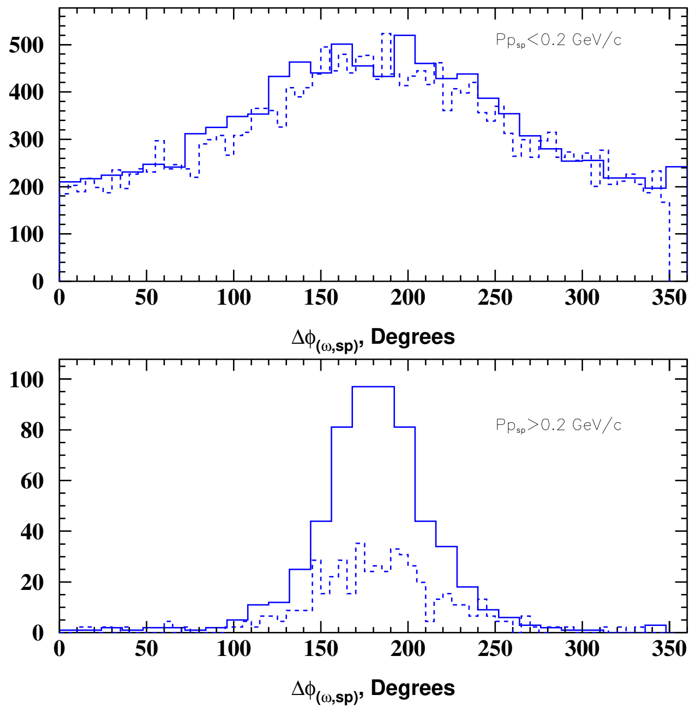

Fig. 22. Angular correlation of the spectator proton with the ω meson (c.f. Fig.11).

9 Requested time for measurements

In the first half of 1999 we intend to install the cluster target at ANKE. Within the commissioning of this target we apply for a few days of beam time for test measurements using a prototype spectator counter as well as the forward detection system for the fast deuterons (see "Request for beam time at ANKE using the cluster target"). As shown in the previous section one can expect to collect sufficient statistics to even extract from the data information on the ω-production cross section.

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