Precision Measurement of the Quasifree $pn \to d\phi$ Reaction Close to Threshold

Y. Maeda,[1,2] M. Hartmann,[1,*] I. Keshelashvili,[1,3] S. Barsov,[4] M. Büscher,[1] A. Dzyuba,[1,4] S. Dymov,[5] V. Hejny,[1]
A. Kacharava,[3,6] V. Kleber,[7] H. R. Koch,[1] V. Koptev,[4] P. Kulessa,[1,8] T. Mersmann,[9] S. Mikirtytchiants,[4] A. Mussgiller,[1,6]
M. Nekipelov,[1] H. Ohm,[1] R. Schleichert,[1] H. J. Stein,[1] H. Ströher,[1] Yu. Valdau,[4] K. H. Watzlawik,[1]
C. Wilkin,[10] and P. Wüstner[11]

[1]*Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[2]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[3]*High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia*
[4]*High Energy Physics Department, Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia*
[5]*Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[6]*Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*
[7]*Physikalisches Institut, Universität Bonn, 53115 Bonn, Germany*
[8]*H. Niewodniczański Institute of Nuclear Physics PAN, 31342 Kraków, Poland*
[9]*Institut für Kernphysik, Universität Münster, 48149 Münster, Germany*
[10]*Physics and Astronomy Department, UCL, Gower Street, London WC1E 6BT, United Kingdom*
[11]*Zentralinstitut für Elektronik, Forschungszentrum Jülich, 52425 Jülich, Germany*

(Received 30 June 2006; published 2 October 2006)

The quasifree $pn \to d\phi$ reaction has been studied at the Cooler Synchrotron COSY—Jülich, using the internal proton beam incident on a deuterium cluster-jet target and detecting a fast deuteron in coincidence with the K^+K^- decay of the ϕ meson. The energy dependence of the total and differential cross sections are extracted for excess energies up to 80 MeV by determining the Fermi momentum of the target neutron on an event-by-event basis. Though these cross sections are consistent with s-wave production, the kaon angular distributions show the presence of p waves at quite a low energy. Production on the neutron is found to be stronger than on the proton but not by as much as for the η meson.

DOI: 10.1103/PhysRevLett.97.142301 PACS numbers: 25.40.Ve, 13.75.Cs, 14.40.Cs

Meson production provides access to the internal structure of baryons and the dynamics of hadronic reactions and thus is an important exploration field for nonperturbative QCD. In proton-proton collisions, meson production has been extensively studied and data are now available on the production of most members of the fundamental pseudoscalar and vector nonets near their respective threshold [1], including the $\pi(140)$, $\eta(547)$, and $\eta'(958)$, as well as the $\rho(770)$, $\omega(782)$, and $\phi(1020)$. The ϕ meson is of particular interest because of its comparatively large mass and its dominant $s\bar{s}$ quark structure. However, in order to study all facets of meson production dynamics, it is necessary to investigate the isospin dependence by precision measurements in both pn as well as pp collisions. In the case of the η meson, such experiments have revealed that the pn production cross section is over 6 times larger than that for pp [2]. Analogous ϕ data are important for nucleon-nucleon production models and also serve as crucial input in the interpretation of nucleon-nucleus and nucleus-nucleus results, where *in-medium* effects are anticipated [3].

In the absence of a free neutron target or a quality neutron beam, quasifree production on deuterium $pd \to dXp_{\text{sp}}$ has often been substituted. Here the reaction is assumed to have taken place on the neutron bound in the deuteron and p_{sp} is a slow "spectator" proton that does not take an active part in the reaction and whose momentum reflects the Fermi motion of the particle before the production. In order to show that the reaction involved only the neutron, the spectator must be identified and the precise determination of the c.m. energy requires that the p_{sp} momentum is well measured. Spectators emerging from an ultrathin target with a few MeV can be studied directly at a storage ring using solid-state counters, as has been done for $pd \to d\pi^0 p_{\text{sp}}$ [4] and $pd \to d\omega p_{\text{sp}}$ [5]. The alternative approach is to identify the produced meson X through its decay products and then reconstruct the spectator momentum using kinematics. This method has been successfully employed for the $pd \to d\eta p_{\text{sp}}$ and $pd \to pn\eta p_{\text{sp}}$ reactions, where the η was identified through its 2γ decay branch [2]. We have studied for the first time quasifree $pn \to d\phi$ production through the indirect method of measuring the spectator momentum using the K^+K^- decay of the ϕ in coincidence with a fast deuteron.

The experiment was performed with a 2.65 GeV proton beam at an internal target station of the Cooler Synchrotron COSY, employing the magnetic spectrometer ANKE [6] to identify and measure the reaction. ANKE has detection systems placed to the right and left of the emerging beam to register slow positively and negatively charged ejectiles, with fast positively charged particles being measured in the forward system. The deuterium cluster-jet target [7] provided areal densities of $\sim 3.4 \times 10^{14}$ cm^{-2}, which, combined with a typical proton beam intensity of

$\sim 6.2 \times 10^{16}$ s^{-1}, gave an integrated luminosity of 23 pb^{-1} over the 300 h of data taking.

The $pd \to d\phi p_{\mathrm{sp}}$ reaction was studied in a manner analogous to that successfully employed for the $pp \to pp\phi$ reaction at COSY [8], using the $\phi \to K^+K^-$ decay. Charged kaon pairs were detected in coincidence with a forward-going deuteron, requiring that the overall missing mass in the reaction was consistent with that of the nonobserved slow spectator proton p_{sp}. As a first step, positive kaons are selected through a procedure described in detail in Ref. [9], using the time of flight (TOF) between start and stop scintillation counters of a dedicated K^+ detection system. In the second stage, both the coincident K^- and forward-going deuteron are identified from the time-of-flight differences between the stop counters in the negative and forward detector systems with respect to the stop counter in the positive system that was hit by the K^+. These two TOF selections, as well as that for the K^+, were carried out within $\pm 3\sigma$ bands.

Figure 1(a), which shows the missing-mass spectrum assuming that the detected particles are indeed K^+, K^-, and deuteron, demonstrates a clear peak at the mass of the proton. The secondary peak around 1.02 GeV/c^2 arises from $p\pi^+\pi^-$ events, where a π^+ was misidentified as a K^+. This background is well separated from the spectator peak over the whole kinematic region. The residue from misidentified particles inside the proton gate (of $\pm 3\sigma$) is 3.1%, and such events generally fail the later criteria of the analysis. In total, about 4500 coincidences were retained as $dK^+K^-p_{\mathrm{sp}}$ events for further study.

The K^+K^- invariant-mass spectrum for the 4500 events is shown in Fig. 1(b). The distribution is dominated by the ϕ meson peak, which sits on a slowly varying physical background from direct K^+K^- production. This has been estimated by a four-body phase-space simulation which, together with the ϕ contribution, is fitted to the overall spectrum. The shape of the resonant contribution is reproduced by the natural width of ϕ meson with an experimental mass resolution $\sigma = 1$ MeV/c^2, which is consistent with the momentum resolution of the ANKE detector system. The direct K^+K^- contribution, which is less than 8% in the ϕ mass region 1.020 ± 0.015 GeV/c^2, could be easily subtracted.

The momentum distribution of the unobserved proton for events in the ϕ peak is shown in Fig. 1(c). As expected for a spectator proton, this spectrum is peaked at very low values and there are few events with momenta above about 150 MeV/c. To confirm the spectator hypothesis, a Monte Carlo simulation has been performed where the Fermi momentum in the target deuteron has been derived from the Bonn potential [10]. The energy dependence of the $pn \to d\phi$ cross section is assumed to follow phase space, which is consistent with the results to be shown later. After including the detector response, the simulation fits very well the shape of the data for momenta up to at least 150 MeV/c, a region where the model dependence of the deuteron wave function is negligible compared with our statistical uncertainty. The spectator distribution could be obtained with even greater precision than that for the corresponding $pd \to d\eta p_{\mathrm{sp}}$ reaction [2].

Because of the Fermi motion of the neutron in the deuteron, the c.m. excess energy $\epsilon = \sqrt{s} - (m_d + m_\phi)$ is spread over a range of values even for a fixed beam energy. Since we have completely determined the kinematics for each of the $pd \to d\phi p_{\mathrm{sp}}$ events, the value of ϵ could be calculated on an event-by-event basis, and the resulting distribution is shown in Fig. 1(d). This is also well described by the simulation, which shows that ϵ can be reconstructed with an average precision of $\sigma_\epsilon = 2$ MeV, and which can be used in the extraction of cross sections for $\epsilon < 80$ MeV.

The target density was determined by measuring the frequency shift of the stored proton beam as it lost energy due to its repeated passages through the target [11]. Combined with measurements of the beam current this yielded the value of the luminosity L with a precision of about $\pm 6\%$. This was checked through the simultaneous measurement of pd elastic and quasielastic scattering, where a fast proton was registered in the polar angular range $5.0° < \vartheta < 8.5°$ in the forward detectors. The lumi-

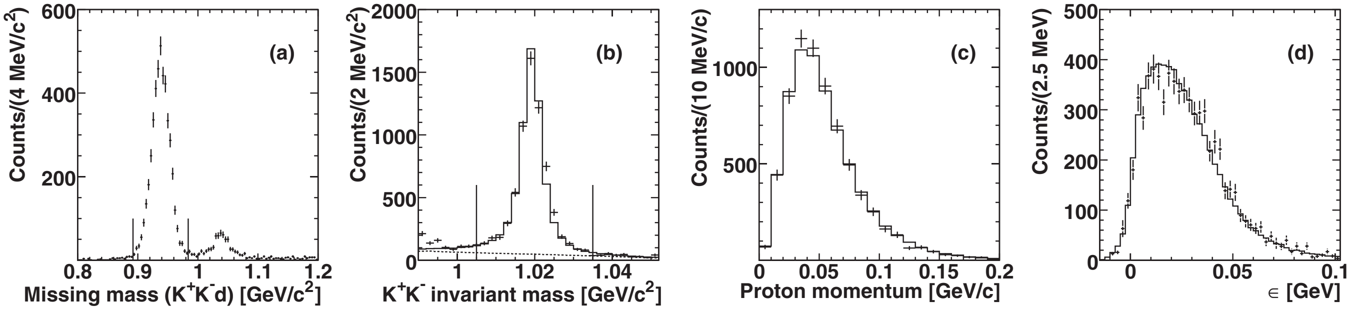

FIG. 1. (a) Missing-mass distribution of the $pd \to dK^+K^-X$ events with lines indicating the proton selection range. (b) K^+K^- invariant-mass distribution with lines showing the mass range of selected ϕ meson events. The dashed curve shows the four-body phase-space fit to the nonresonant production, while the solid histogram is the sum of this and the ϕ meson contribution. (c) Momentum distribution of the unobserved proton compared with a Monte Carlo simulation based on the spectator model. (d) Distribution in c.m. excess energy compared with the same simulation.

nosity was then obtained from estimates [12] of the corresponding differential cross sections within the Glauber formalism [13]. This technique has been used successfully at other energies [14]. Though the two methods give consistent results to within 3%, the error in the pd technique is about 10%, due mainly to the use of the theoretical model and uncertainty in the acceptance correction.

In order to evaluate differential cross sections, the geometrical acceptance, resolution, detector efficiency, and kaon decay probability were taken into account in a Monte Carlo simulation, using the GEANT4 package [15]. For a given excess energy, the distributions in all variables were consistent with phase space except for that of Θ_ϕ^K, which is the polar angle of the K^+ from the ϕ decay with respect to the beam direction, in the ϕ rest frame. At threshold the only allowed $pn \to d\phi$ transition arises from an initial ${}^1P_1$ state. The unique production amplitude is therefore of the form $M = \boldsymbol{p} \cdot (\boldsymbol{\varepsilon}_d^\dagger \times \boldsymbol{\varepsilon}_\phi^\dagger)\Phi_{pn}$, where $\boldsymbol{p}$ is the beam momentum, $\boldsymbol{\varepsilon}_d$ and $\boldsymbol{\varepsilon}_\phi$ are the polarization vectors of the deuteron and ϕ respectively, and Φ_{pn} represents the spin-0 initial pn state. From the structure of the matrix element, it follows that the ϕ meson is aligned transversally to the beam so that, following its decay, the kaons cannot be produced along the beam direction and a $\sin^2\Theta_\phi^K$ behavior is to be expected.

To allow for the possibility of higher partial waves, the distribution was parametrized in the most general allowed form: $d\sigma/d\Omega_\phi^K = 3(a\sin^2\Theta_\phi^K + 2b\cos^2\Theta_\phi^K)/8\pi$, normalized such that the total cross section $\sigma = a + b$. This form was handled iteratively in the simulation to get the best values of the parameters a and b and of the ANKE acceptance. For large ϵ the acceptance in the backward c.m. hemispheres is somewhat higher than in the forward, but all distributions are completely consistent with them being symmetric in the c.m. system. The results for different excess energy bins in Fig. 2 are therefore shown as functions of the magnitudes of the cosines of Θ_ϕ^K and the polar angle $\Theta_{\text{c.m.}}^\phi$ of the ϕ, for which the resolutions are estimated to be 0.024 and typically 0.02–0.04, respectively. The dominance of the $\sin^2\Theta_\phi^K$ term is very clear at the lower energies, and all the data are well represented by $b/a \approx (0.012 \pm 0.001)(\epsilon/\text{MeV})$. Given the ambiguity associated with the nine possible p-wave amplitudes, this ratio represents the minimum fraction of higher partial waves and indicates that this is significant for the larger ϵ. Despite this, the angular distribution of ϕ production in the overall c.m. system is consistent with isotropy for all ϵ. Note that the production of p-wave ϕ from an initial ${}^3S_1$ state would also be flat in $\cos\Theta_{\text{c.m.}}^\phi$.

The values of the a and b coefficients lead directly to the total cross section for ϕ production shown in Fig. 3, while numerical values will be found in the High Energy Physics database [16]. In addition to the point-to-point statistical errors, there is an overall systematic uncertainty of ±10% coming from luminosity (6%), stability of the data-taking efficiency (4%), background (3%), and track reconstruction efficiency corrections for kaon detection (4%). The results have not been corrected for the reduction in the incident flux due to shadowing by the proton in the deuteron target, which would increase the cross sections by about 4% [17]. Values of the $pp \to pp\phi$ total cross sections available in our energy range are also shown [8].

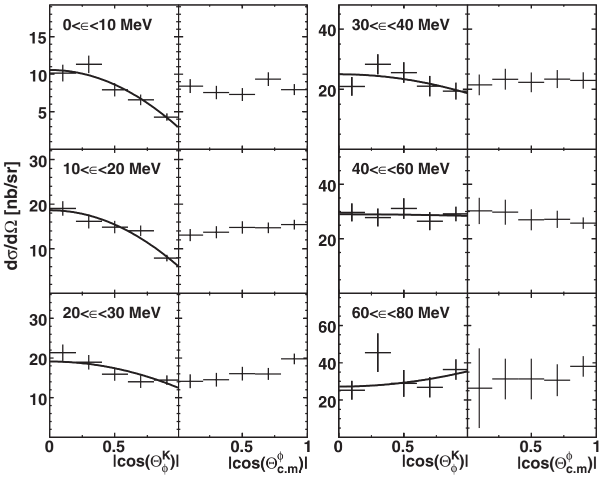

FIG. 2. Differential cross sections for $pn \to d\phi$ for different ranges of excess energy, with the left panels showing the dependence on the angle of the K^+ from the ϕ decay in the ϕ rest frame, and the right panels the dependence on the polar angle of the ϕ in the overall c.m. system. Vertical error bars indicate purely statistical uncertainties, whereas the horizontal ranges reflect the bin width.

Two-body phase space increases like $\sqrt{\epsilon}$, and this is distorted by less than 4% when the width of the ϕ meson is taken into account. As shown in Fig. 3, we find that $\sigma(pn \to d\phi) = (48 \pm 1)\sqrt{(\epsilon/\text{MeV})}$ nb, despite the decay angular distributions showing significant p-wave effects at higher ϵ. The values are much higher than those of

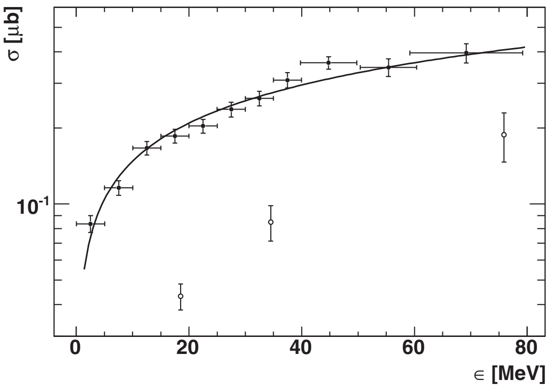

FIG. 3. Total cross section for the quasifree $pn \to d\phi$ reaction as a function of the excess energy (solid circles). In addition to the statistical error bars shown, there are overall systematic uncertainties of ±10%. The curve represents a phase-space $\sqrt{\epsilon}$ behavior. For comparison, we also show as open circles the values obtained from $pp \to pp\phi$ [8].

$pp \to pp\phi$ [8,18], but this is due in part to there being a three- rather than a two-body final state. However, very near threshold, isoscalar S-wave ϕpn production can be estimated from our $d\phi$ data using final-state-interaction theory [19], a technique that has been tested for η production [2]. This approach yields $\sigma(pn \to pn\phi)/\sigma(pp \to pp\phi) \approx 2.3 \pm 0.5$, which is only about a third as big as the ratio for η production [2].

The ratio $R_{\phi/\omega}$ of the production of the light isoscalar vector mesons ϕ and ω in various nuclear reactions involving nonstrange particles provides valuable tests of the Okubo-Zweig-Iizuka (OZI) rule [20]. This rule suggests that, due to small deviations from ideal mixing of these mesons at the quark level, one should have $R_{\phi/\omega} \approx R_{\mathrm{OZI}} = 4.2 \times 10^{-3}$ [21] under similar kinematic conditions. Significant enhancements of this ratio have, however, been reported in the literature, and for proton-proton collisions we recently obtained $\sigma(pp \to pp\phi)/\sigma(pp \to pp\omega) = (3.3 \pm 0.6) \times 10^{-2} \approx 8 \times R_{\mathrm{OZI}}$ [8]. There is a measurement of ω production in proton-neutron collisions at 57^{+21}_{-15} MeV [5], and comparing this with our data, we find that at this energy $\sigma(pn \to d\phi)/\sigma(pn \to d\omega) = (4.0 \pm 1.9) \times 10^{-2} \approx 9 \times R_{\mathrm{OZI}}$. Though similar to the pp result, the error bar is large.

In near-threshold production reactions, the relevant degrees of freedom seem to be mesons and baryons rather than quarks and gluons, and the predictions for ϕ production in $pn \to d\phi$ are very sensitive to meson exchange and nucleonic currents [22–24]. Nevertheless, all three calculations yield broadly similar values for the $pn \to d\phi$ total cross section, being in the 0.1–0.5 μb range at $\epsilon \approx 50$ MeV compared with the $\approx$0.34 μb shown by our data in Fig. 3. However, whereas one calculation suggests that the ϕ production is maximal in the forward direction [24], another predicts it to be much flatter [22]. Our data in Fig. 2 are consistent with isotropy. Although no calculations appear to exist in the literature for the polarization of the ϕ meson in the $pn \to d\phi$ reaction, estimates have been made for that of the deuteron and of the initial pn spin correlation [24]. Both of these observables are sensitive to effects from p-wave ϕ production but neither shows as big effects with energy as we have seen from the ϕ alignment in Fig. 2.

In summary, we have presented the first measurements of ϕ production in pn collisions that will provide important constraints on the theoretical modeling of such processes. The ϕ polarization, as measured through its K^+K^- decay, shows the early onset of p waves which are not apparent in the energy variation of the total cross section. This behavior also cannot be seen in the c.m. angular distributions, and this suggests that p waves might be more important than previously thought in other near-threshold meson production. The production is stronger in pn collisions than in pp, though the factor is not as large as for η production.

These data are, of course, valuable in the interpretation of ϕ meson production in the collision of heavy ions. Further testing of the OZI rule in pn collisions will have to await better data on ω production. This should be possible in the future at the WASA (Wide Angle Shower Apparatus) at the COSY facility [25], where photons from the $\omega \to \pi^0\gamma$ decay can be detected in coincidence with fast deuterons. This decay mode would also allow the polarization of the ω to be analyzed to see if this also shows a rapid onset of p waves.

Support from J. Haidenbauer, C. Hanhart, U.-G. Meißner, A. Sibirtsev, Yu. Uzikov, K. Nakayama, and other members of the ANKE Collaboration, as well as the COSY machine crew, is gratefully acknowledged. This work has been partially financed by the BMBF, DFG, Russian Academy of Sciences, and COSY FFE.

---

*Electronic address: M.Hartmann@fz-juelich.de

[1] C. Hanhart, Phys. Rep. **397**, 155 (2004).
[2] H. Calén *et al.*, Phys. Rev. Lett. **80**, 2069 (1998); Phys. Rev. C **58**, 2667 (1998).
[3] G. E. Brown and M. Rho, Phys. Rep. **269**, 333 (1996).
[4] R. Bilger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **457**, 64 (2001).
[5] S. Barsov *et al.*, Eur. Phys. J. A **21**, 521 (2004).
[6] S. Barsov *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 364 (2001).
[7] A. Khoukaz *et al.*, Eur. Phys. J. D **5**, 275 (1999).
[8] M. Hartmann *et al.*, Phys. Rev. Lett. **96**, 242301 (2006).
[9] M. Büscher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **481**, 378 (2002).
[10] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).
[11] K. Zapfe, Nucl. Instrum. Methods Phys. Res., Sect. A **368**, 293 (1996).
[12] Yu. Uzikov (private communication).
[13] V. Franco and R. J. Glauber, Phys. Rev. **142**, 1195 (1966).
[14] V. Komarov *et al.*, Phys. Lett. B **553**, 179 (2003).
[15] S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003); S. Giani *et al.*, computer code GEANT4, 2005, http://geant4.web.cern.ch/geant4/.
[16] Durham Database Group, http://durpdg.dur.ac.uk/HEPDATA/
[17] E. Chiavassa *et al.*, Phys. Lett. B **337**, 192 (1994).
[18] F. Balestra *et al.*, Phys. Rev. C **63**, 024004 (2001).
[19] G. Fäldt and C. Wilkin, Phys. Lett. B **382**, 209 (1996).
[20] S. Okubo, Phys. Lett. **5**, 165 (1963); G. Zweig, CERN Report No. TH-401, 1964; J. Iizuka, Prog. Theor. Phys. Suppl. **37–38**, 21 (1966).
[21] H. J. Lipkin, Phys. Lett. **60B**, 371 (1976).
[22] K. Nakayama, J. Haidenbauer, and J. Speth, Phys. Rev. C **63**, 015201 (2000).
[23] V. Yu. Grishina, L. A. Kondratyuk, and M. Büscher, Phys. At. Nucl. **63**, 1824 (2000).
[24] L. P. Kaptari and B. Kämpfer, Eur. Phys. J. A **14**, 211 (2002); **23**, 291 (2005).
[25] H.-H. Adam *et al.*, nucl-ex/0411038.