

1-1-2004

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Repository Citation

McCormick, K.; Biselli, Angela; and CLAS Collaboration, "Tensor polarization of the ϕ meson photoproduced at high t " (2004). *Physics Faculty Publications*. 92.

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Published Citation

K. McCormick et al. [CLAS Collaboration], "Tensor polarization of the ϕ meson photoproduced at high t ", *Physical Review C* 69.3 (2004) DOI: 10.1103/PhysRevC.69.032203

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Tensor polarization of the ϕ meson photoproduced at high t

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(Received 11 November 2003; published 22 March 2004)

As part of a measurement [E. Anciant *et al.*, Phys. Rev. Lett. **85**, 4682 (2000)] of the cross section of ϕ meson photoproduction to high momentum transfer, we measured the polar angular decay distribution of the outgoing K^+ in the channel $\phi \rightarrow K^+K^-$ in the ϕ center-of-mass frame (the helicity frame). We find that s -channel helicity conservation (SCHC) holds in the kinematical range where t -channel exchange dominates (up to $-t \sim 2.5 \text{ GeV}^2$ for $E_\gamma = 3.6 \text{ GeV}$). Above this momentum, u -channel production of a ϕ meson dominates and induces a violation of SCHC. The deduced value of the ϕNN coupling constant lies in the upper range of previously reported values.

DOI: 10.1103/PhysRevC.69.032203

PACS number(s): 13.60.Le, 12.40.Nn, 13.40.Gp

The photoproduction of ϕ mesons at high momentum transfer $-t = -(k_\gamma - k_\phi)^2$ preferentially selects two-gluon exchange mechanisms [1,2]. The reason is that valence quark exchange mechanisms are strongly suppressed due to the dominant $s\bar{s}$ component of the ϕ meson and the conjectured small strange component in the nucleon wave function. However, a small nonstrange component in the ϕ meson wave function (as revealed by the $\phi \rightarrow \pi\gamma$ radiative decay) or a possible strange component in the nucleon wave function make possible a direct coupling of the ϕ meson to the nucleon, allowing nucleon exchange mechanisms to show up in a well-defined part of the phase space. This happens at

backward angles [high $-t$ but low $-u = -(2m_N^2 + m_\phi^2 - s - t)$], as demonstrated by the differential cross section that was previously reported in Ref. [1].

In this paper we report on the analysis of the angular decay distribution of the ϕ meson over the entire range of momentum transfer accessible at $E_\gamma = 3.6 \text{ GeV}$. This was made possible by the combined use of the large acceptance of the CLAS (CEBAF Large Acceptance Spectrometer) detector [3] and of the intense tagged-photon beam [4] at Jefferson Laboratory (JLab). For the first time momentum transfers as large as $-t = 4 \text{ GeV}^2$ have been reached, in contrast with a previous measurement [5] that was restricted to values below 1 GeV^2 . This decay angular distribution adds more constraints to the reaction mechanism, since two-gluon exchange is expected to satisfy s -channel helicity conservation (SCHC), while u -channel nucleon exchange is not. It leads to the determination of the ϕNN coupling constant, relative to ωNN , and provides one more constraint on a possible strange content of the nucleon.

The decay distribution of the vector meson will be presented in its helicity system: the z direction is chosen opposite to the direction of the outgoing nucleon in the vector meson rest frame. The decay angles θ and ϕ are, respectively, the polar and azimuthal angles of the K^+ .

Assuming pure ϕ meson production, the decay angular distribution is given by [6]

$$\frac{dN}{d \cos \theta d\phi} = W^0(\cos \theta, \phi) + \sum_{\alpha=1}^3 P_\gamma^\alpha W^\alpha(\cos \theta, \phi). \quad (1)$$

For unpolarized photons, only the first term survives. Integrating over the azimuthal angle ϕ , the decay angular distribution can then be written as

$$\frac{dN}{d\theta} = \frac{3}{4} \sin \theta [(1 - \rho_{00}^0) \sin^2 \theta + 2\rho_{00}^0 \cos^2 \theta]. \quad (2)$$

The tensor polarization matrix element ρ_{00}^0 describes the probability that a longitudinally polarized ϕ meson is produced by a transverse real photon. If SCHC holds then this

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term is zero and there is no contribution from longitudinally polarized ϕ 's; in this case the angular distribution exhibits a $\sin^3\theta$ dependence.

The ϕ meson may interfere with the underlying K^+K^- continuum. Assuming an S wave continuum (as expected to dominate near the threshold), the decay angular distribution becomes

$$\frac{dN}{d\theta} = \frac{3}{4}[(1 - \rho_{00}^0)\sin^3\theta + 2\rho_{00}^0 \cos^2\theta \sin\theta] + \alpha \cos\theta \sin\theta + \frac{1}{2}\kappa \sin\theta. \quad (3)$$

The second term, proportional to α , describes the interference between any longitudinal ϕ 's and the S -wave K^+K^- continuum, while the third describes the S -wave continuum of strength κ .

As described in the following sections, the angular decay distribution of the K^+ in the ϕ meson center-of-mass frame was measured for eight bins in t . The resulting distributions were fitted with Eq. (3) to extract values of ρ_{00}^0 and α .

For this measurement, a 4.1 GeV electron beam was incident on a gold radiator of 10^{-4} radiation lengths, producing a bremsstrahlung photon beam that was tagged in the energy range of 3.3–3.9 GeV. A photon tagging system [4] detected the scattered electrons, with a resolution of 0.1 % of the incident beam energy. The photon beam was then incident on a liquid-hydrogen target, contained in a mylar cylinder 6 cm in diameter and 18 cm long, which was maintained at 20.4 K. The photon flux was determined with a pair spectrometer located downstream of the target, which was calibrated via comparison to a total absorption counter.

The hadrons were detected in the CLAS spectrometer [3]. The toroidal field of CLAS is generated with a six-coil superconducting magnet, effectively leading to six independent spectrometers capable of measuring particles with polar angles between 10° and 140° , thus detecting a large fraction of the ϕ mesons produced at high $-t$. Particle momenta are determined via magnetic analysis using trajectories reconstructed in the drift chambers [7], and particle identification is accomplished via time-of-flight techniques using scintillators [8] that surround the toroid.

The ϕ meson decay into a K^+K^- pair was identified through the missing mass in the reaction $\gamma p \rightarrow pK^+(X)$. This technique is preferable to measuring the K^- directly, since, due to the magnetic field configuration, negative particles can be deflected into the inert forward region of CLAS where they are lost.

Figure 1 shows the missing mass in the reaction $\gamma p \rightarrow pK^+(X)$. A well-defined K^- peak can be seen above a background that corresponds to a combination of misidentified pions, the contributions of multiparticle channels and accidentals between CLAS and the tagger. The multiparticle background is thought to come mostly from multipion channels such as $\gamma p \rightarrow p\pi^+(\pi^-\pi^0)$. For these types of channels, if the π^+ is misidentified as a K^+ , then the missing mass of the remaining two pion system can be close to that of a K^- , leading to a background event.

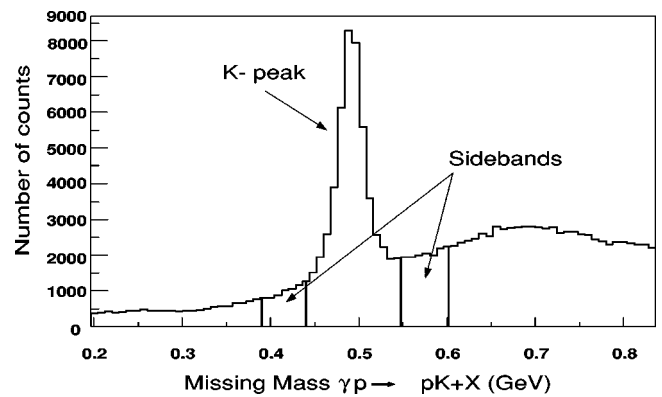


FIG. 1. Missing mass in the reaction $\gamma p \rightarrow pK^+(X)$.

For each event in the K^- peak, the K^+K^- invariant mass is then calculated (see Fig. 2). For the events whose invariant masses fall within the ϕ meson mass peak (1–1.050 GeV), the polar angle of the K^+ in the ϕ meson center-of-mass frame is calculated. As noted above, if this angle exhibits a $\sin^3\theta$ distribution, then SCHC holds. The events that come from the background under the K^- peak must still be subtracted from the angular decay distribution. This is done by calculating the invariant mass for each of the events in the sidebands (upper and lower, respectively), assuming that the mass of the missing particle is the average mass of the sideband under consideration. The thresholds for the different reactions being considered, $\gamma p \rightarrow pK^+K^-$ and $\gamma p \rightarrow pK^+X$, vary according to the mass, as can be seen in Fig. 2, which shows the invariant mass distributions of the two sidebands. To take the varying kinematics into account, the contributions of the sidebands are taken at the same distance from their corresponding threshold. For these events the angle of the K^+ in the helicity frame of the K^+X system is calculated, yielding an angular distribution for the upper and lower sidebands.

Figure 3 shows the decay angular distributions of the ϕ meson events before subtraction (solid curves), along with the events resulting from each sideband. The angular distri-

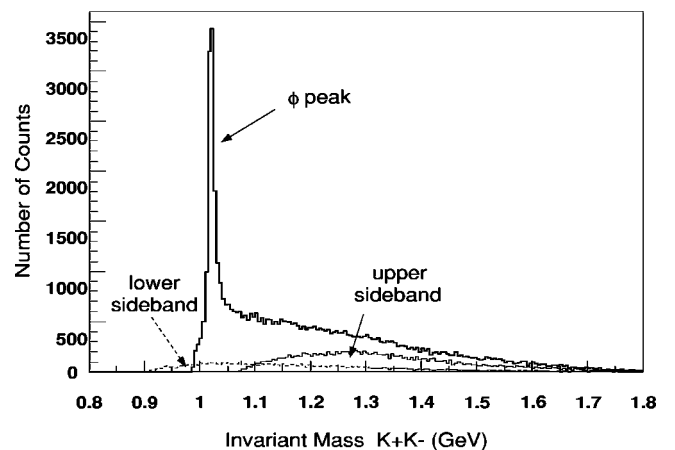


FIG. 2. Invariant mass of the K^+K^- pair. The invariant mass of the events that fall into the lower sideband of the K^- distribution are shown as the dotted curve, the ones of the upper sideband as the solid curve.

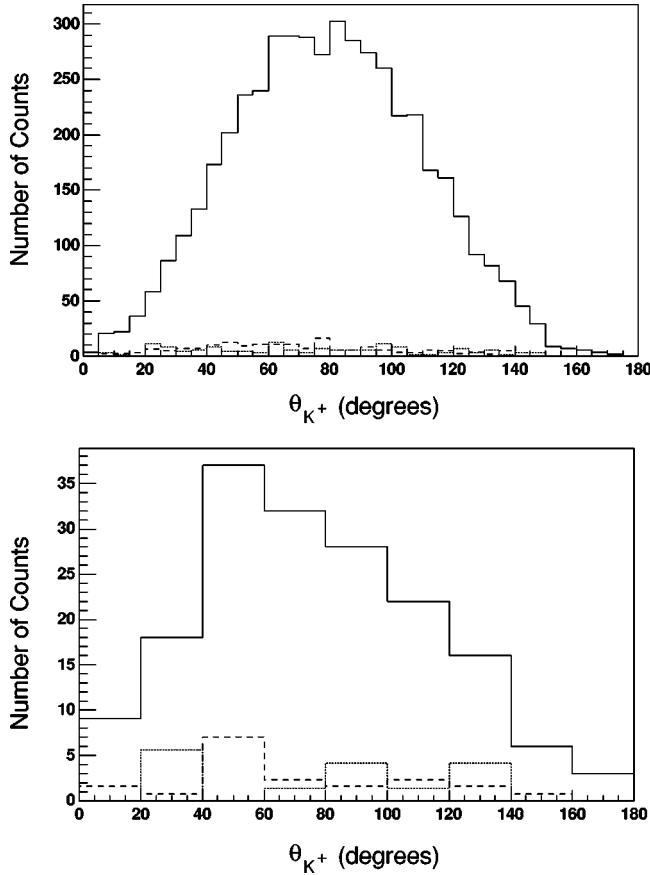


FIG. 3. The unsubtracted ϕ meson decay distribution (solid line) is compared to the lower (dotted) and upper (dashed) sideband distributions. The top plot corresponds to $0.4 < -t < 0.7 \text{ GeV}^2$, while the bottom plot corresponds to $2.7 < -t < 3.5 \text{ GeV}^2$. Θ_{K^+} is the polar angle of the K^+ in the ϕ meson at rest system.

butions for the left and right sidebands are subtracted separately from the distribution resulting from the ϕ meson events. Within the statistics the sideband distributions are the same. At all values of $-t$ the background subtraction is small. At low values of $-t$, the sideband contribution is negligible, and at the highest values of $-t$ the subtraction does not significantly change the shape of the decay distribution. The decay distributions are then corrected for the CLAS angular efficiency in a given bin in $-t$, according to the method described in Ref. [1]. The corresponding correction is almost the same in each bin in $-t$ and varies from 0.70 (forward angles) to 1.30 (backward angles): the net effect is to make the ϕ meson decay angular distribution more symmetric. Some sample angular distributions are shown in Fig. 4 for four different bins in $-t$. All together eight bins in $-t$ were measured, spanning $0.4 \leq -t \leq 5.0 \text{ GeV}^2$.

The extraction of ρ_{00}^0 and α was done by fitting the angular decay distribution of the ϕ mesons with the left and right sideband contributions subtracted separately for two different hypotheses for the continuum: (see Ref. [1]) either a flat contribution or a phase space distribution plus a contribution from the $f_0(980)$. The ratio of the ϕ to the continuum, κ , was imposed in the fitting procedure and taken from the data (Fig. 5 of Ref. [1]). The four values for ρ_{00}^0 and α resulting

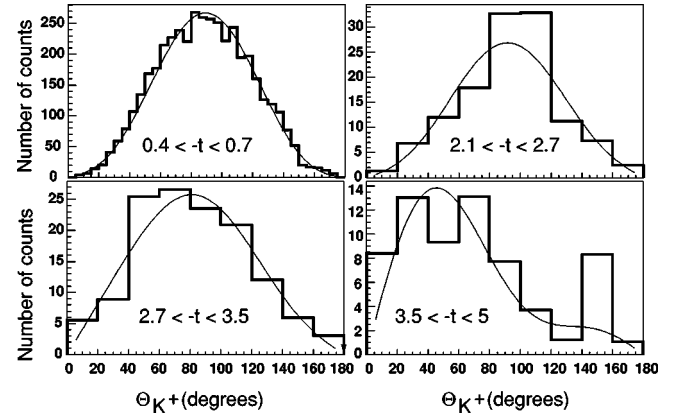


FIG. 4. The distribution of the polar angle of the K^+ in the ϕ meson at rest system for four different bins in $-t$, after background subtraction. The data are represented by the histograms, while the curves are the result of the fit according to Eq. (3).

from these fits were then averaged. The results are shown in Fig. 5. The error bars indicate the spread in the raw values due to the sideband and continuum subtraction.

Also shown in Fig. 5 are the calculations of Ref. [9]. The dashed curve corresponds to the exchange of two nonperturbative gluons. It dominates the differential cross section [1] and obeys SCHC. The distributions confirm the expectation, showing that there is essentially no violation of s -channel

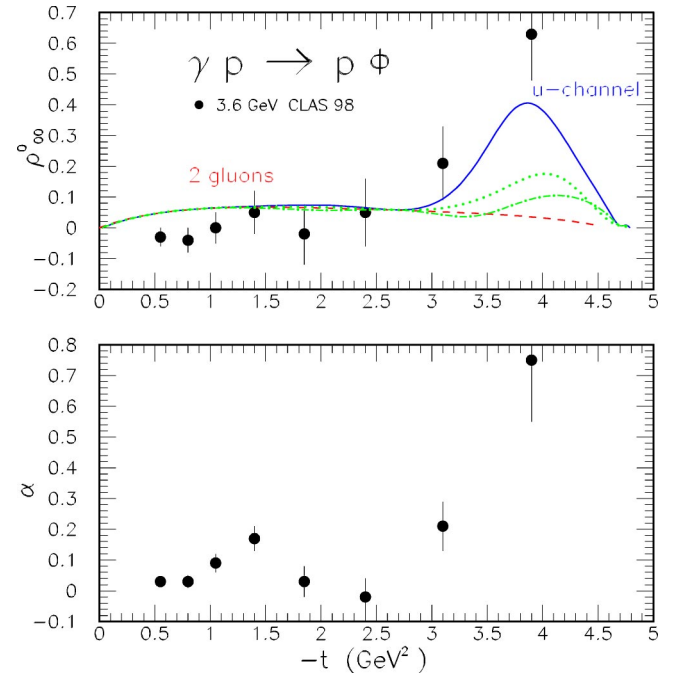


FIG. 5. (Color online) The values for ρ_{00}^0 and α extracted from the decay angular distribution of the K^+ in the ϕ meson center-of-mass system. As described in the text, the error bars show the spread in the values taking different hypotheses for the background subtraction. Also shown are the calculations of Ref. [9]. The dashed curve models pomeron exchange as the exchange of two nonperturbative gluons. The solid curve includes the u -channel contribution with $g_{\phi NN}=3$. The dotted curve corresponds to $g_{\phi NN}=1$, while the dash-dotted curve corresponds to $g_{\phi NN}=-3$.

helicity conservation at lower momentum transfers. Above $-t \sim 2.5 \text{ GeV}^2$, the u -channel contribution to ϕ meson production (solid line in Fig. 5) begins to dominate and a large violation of SCHC is observed. The values for α are shown in the lower part of the figure. They indicate the interference between the helicity zero ϕ meson and the S -wave K^+K^- continuum. It comes as no surprise that the interference term α is strongly correlated with the SCHC violation seen in the ρ_{00}^0 distribution.

The expression of the amplitude for the exchange of the nucleon Regge trajectory in the u channel is given by Eq. (9) of Ref. [9]. Due to isospin considerations, this is the only leading trajectory that can be exchanged in the u channel in ϕ as well as in ω photoproduction. Since the nucleon pole lies far from the physical region, an off-shell form factor takes care of the necessary extrapolation [10] and reduces the amplitude by about 33%. In the ω channel, all the coupling constants are known, and a fair agreement [9–12] with ω photoproduction cross sections at backward angles is achieved with $g_{\omega NN} = g_V(1 + \kappa_V) = -15$ ($\kappa_V = 0$). This value already led to a good accounting of π^0 photoproduction [13] and falls within the range of accepted values in the literature [14].

When applying this model to the ϕ channel, the only unknown parameter is the ϕNN coupling constant. The choice $g_{\phi NN} = 3$ ($\kappa_V = 0.3$) not only leads to a good accounting of the rise of the differential cross section at backward angles [1] but also of ρ_{00}^0 at backward angles (solid curve). A more robust quantity is the ratio $g_{\omega NN}/g_{\phi NN} = -5$, which gets rid of possible uncertainties in the extrapolation to the nucleon pole.

The same value was found in the analysis of nucleon electromagnetic form factors [15], as well as the analysis of

nucleon-nucleon and hyperon-nucleon scattering [16]. It is higher than the value $g_{\phi NN} = 1$, or $|g_{\omega NN}/g_{\phi NN}| = 15$, which is predicted assuming a minimal ω - ϕ mixing, as represented by the ratio of the radiative decay constant $\omega \rightarrow \gamma\pi$ and $\phi \rightarrow \gamma\pi$. As shown by the dotted curve in Fig. 5, this smaller value badly misses the backward peak. Also a negative sign of the coupling constant is excluded by the data (dash-dotted curve). This minimal ω - ϕ mixing comes from the small non-strange quark component in the ϕ meson wave function (and, correspondingly, from the small strange quark component in the ω wave function). It allows the establishment of the relation of the coupling constants of these mesons with the nucleon, assuming that the nucleon wave function does not contain strange quarks. If it does, then the ϕ meson can couple directly to the nucleon and the coupling constant $g_{\phi NN}$ is enhanced. The large value of the ϕNN coupling constant found in this work implies that strange quarks are present in the nucleon ground state wave function.

In summary, we have determined the first matrix element ρ_{00}^0 of the tensor polarization of the ϕ , up to $-t = 4 \text{ GeV}^2$, in the full momentum transfer range available at $E_\gamma = 3.6 \text{ GeV}$. SCHC holds up to $-t = 2.5 \text{ GeV}^2$, above which deviations point toward a value of the ϕ meson nucleon coupling constant in the upper range of values already reported.

The Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility under Department of Energy Contract No. DE-AC05-84ER40150. This work was supported in part by the French Commissariat à l’Energie Atomique, the Italian Istituto Nazionale di Fisica Nucleare, the U.S. Department of Energy and National Science Foundation, and the Korea Science and Engineering Foundation.

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