Photoproduction of $\phi(1020)$ Mesons on the Proton at Large Momentum Transfer

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The cross section for ϕ meson photoproduction on the proton has been measured for the first time up to a four-momentum transfer $-t = 4$ GeV^2, using the CLAS detector at the Thomas Jefferson National Accelerator Facility. At low four-momentum transfer, the differential cross section is well described by Pomeron exchange. At large four-momentum transfer, above $-t = 1.8$ GeV^2, the data support a model where the Pomeron is resolved into its simplest component, two gluons, which may couple to any quark in the proton and in the ϕ.

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In this paper we report results of the first determination of the cross section for elastic ϕ photoproduction on the proton, up to $-t = 4$ GeV^2. The scarce existing experimental data for this reaction [1–5] extend only to a momentum transfer of $-t = 1$ GeV^2 and are well described as a purely diffractive process in the framework of the traditional vector dominance model [6], or in a more modern way as the exchange of the Pomeron trajectory in the t channel [7]. At larger t, the small impact parameter makes it possible for quark in the vector meson and a quark in the proton to become close enough to exchange two gluons which do not have enough time to reinteract to form a Pomeron. Such a model of the Pomeron as two nonperturbative gluons [8] matches the diffractive contribution up to $-t = 1$ GeV^2, but predicts a different behavior at higher t [9].

Large momentum transfers also select configurations in which the transverse distances between the two quarks in the vector meson and the three quarks in the proton are small. In that case, each gluon can couple to different quarks of the vector meson [9], as depicted in the middle diagram of Fig. 1, as well as to two different quarks of the proton [10] (bottom diagrams in Fig. 1). Because of the dominant $s\bar{s}$ component of the ϕ, and to the extent that the strangeness component of the nucleon is small, the exchange of quarks is strongly suppressed. So, elastic ϕ photoproduction at large t is a good tool to resolve the Pomeron into its simplest two-gluon component and to gain access to the quark correlation function in the proton [11–13].

Measurements at such large four-momentum transfers are now possible thanks to the continuous beam of CEBAF at Jefferson Lab. This experiment was performed using the Hall B tagged photon beam. The incident electron beam, with an energy $E_0 = 4.1$ GeV, impinged upon a gold radiator of 10^{-4} radiation lengths. The tagging system, which gives a photon-energy resolution of 0.1% E_0, is described in Ref. [14]. For this experiment the photons were tagged only in the range 3.3–3.9 GeV. The target cell, a mylar cylinder 6 cm in diameter and 18 cm long, was filled with liquid hydrogen at 20.4 K.

The photon flux was determined with a pair spectrometer located downstream of the target. The efficiency of this pair spectrometer was measured at low intensity (10^5 γ/s in the entire bremsstrahlung spectrum) by comparison with a total absorption counter (a lead-glass detector of 20 radiation lengths). During data taking at high intensity (6×10^6 tagged γ/s), the number of coincidences, true and accidental, between the pair spectrometer and the tagger was recorded by scalers. The number of photons lost in the target and along the beam line was evaluated with a GEANT simulation. The correction is of the order of 5%. The systematic uncertainty on the photon flux has been estimated to be 3%.

The hadrons were detected in CLAS, the CEBAF large acceptance spectrometer [15]. It consists of a six-coil superconducting magnet producing a toroidal field. Three sets of drift chambers allow the determination of the momenta of the charged particles with polar angles from 10° to 140°. A complete coverage of scintillators allows the discrimination of particles by a time-of-flight technique as described in Ref. [16]. As the field in the magnet was set to bend the positive particles outwards, most of the K^-, from the $\phi \to K^+K^-$ decay, were lost into the inert forward part of the detector. They were always identified by the missing mass of the reaction $\gamma p \to pK^+(X)$.

In Fig. 2, a well-identified K^- peak can be seen above a background which corresponds to a combination of misidentified particles, the contribution of multiparticle channels and accidentals between CLAS and the tagger. This background is eliminated by subtracting the counts

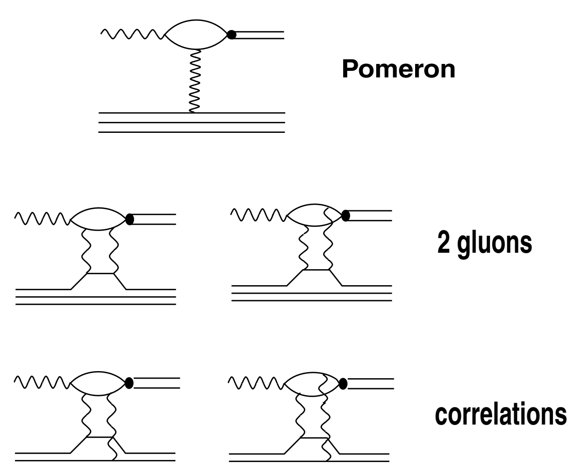

FIG. 1. Diagrams representing the exchange of a Pomeron or of two gluons in the photoproduction of the ϕ.

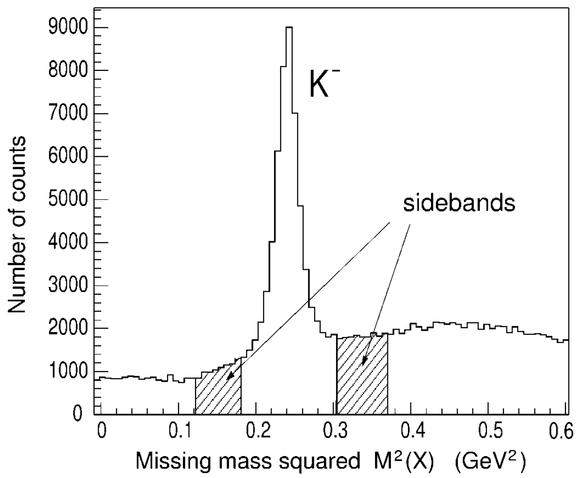

FIG. 2. Missing mass squared $M^2(X)$ in the reaction $\gamma p \rightarrow pK^+(X)$.

in the sidebands from the main peak, in each bin in t (determined by the four momentum of the detected proton). As indicated in the figure, each sideband spans half of the missing mass width under the K^- peak. Their contribution to the K^+K^- mass spectrum is shown in Fig. 3. Note that it is very small under the ϕ peak.

In the Dalitz plot (Fig. 4) of invariant masses squared $M^2(K^+K^-)$ versus $M^2(pK^-)$, two resonant contributions to the pK^+K^- channel can be clearly seen, namely, the $p\phi$ and the $\Lambda^*(1520)K^+$ channels. A cut at $M^2(pK^-) > 2.56$ GeV^2 further suppresses the contribution of the Λ^* production to the K^+K^- mass spectrum.

The resulting mass spectra are shown in Fig. 5 for selected bins in t. The peak of the $\phi(1020)$ clearly shows up over a K^+K^- continuum contribution which must be subtracted. The ϕ events are selected by the cut $1.0 < M^2(K^+K^-) < 1.1$ GeV^2. The CLAS acceptance in the forward direction limits the data set to values of $-t$ larger than 0.4 GeV^2. This experiment extends the measured range up to $-t = 4$ GeV^2.

The detector efficiency depends on four variables: E_γ, t, $\theta^{\rm cm}_{K^+}$, and $\phi^{\rm cm}_{K^+}$ (the decay angles of the K^+ in the c.m. of the ϕ). A GEANT simulation program, which takes into account the entire CLAS setup, was used to calculate the detector efficiency, taking into account in an iterative way the experimentally observed variation of the cross section as a function of these variables. No variations of the cross section against E_γ and $\phi^{\rm cm}_{K^+}$ were observed. This efficiency varies from 0.15 to 0.25. The accuracy of the simulation has been evaluated to be 5% from a comparison between the real data and the Monte Carlo simulation [17] for the channel $\gamma p \rightarrow p\pi^+\pi^-$, where the statistics are very high.

The continuum background has been subtracted assuming an isotropic distribution in $\theta^{\rm cm}_{K^+}$ and two hypotheses for its variation against the mass $M(K^+K^-)$: (i) a flat contribution, and (ii) a phase space distribution plus a contribution of the $f_0(980)$ decaying into two kaons (the mass of the f_0 is below the two-kaon threshold but because of its ~60 MeV width, the tail of the Breit-Wigner can contribute). Its contribution was determined by fitting the K^+K^- mass spectrum [up to $M^2(K^+K^-) = 1.2$ GeV^2 in each bin in t] with two components: the background itself and a Breit-Wigner describing the ϕ meson peak.

The results for the cross section are the average between two values obtained according to these two background hypotheses, with the difference being taken as an estimate of the systematic uncertainty due to the subtraction of the K^+K^- continuum production. The data are integrated over the full tagging energy range ($3.3 < E_\gamma < 3.9$ GeV).

The cross sections $d\sigma/dt$ versus t for the ϕ photoproduction are presented in Fig. 6, for eight bins in t. For values of $-t$ around 1 GeV^2, our data are in good agreement with the most precise published data. The dotted curve corresponds to Pomeron exchange [11]. The solid curve

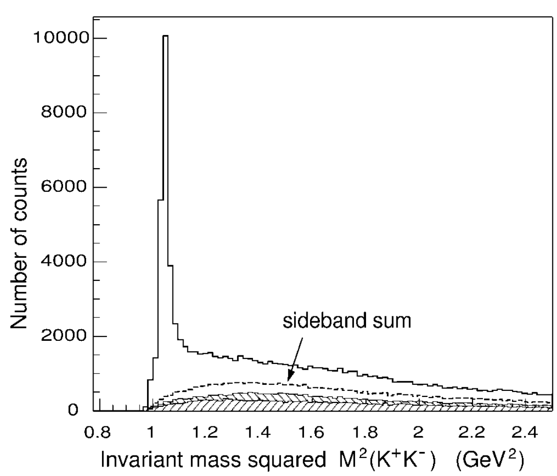

FIG. 3. The K^+K^- mass spectrum, before the sideband subtraction. Slashes: lower mass sideband contribution. Backslashes: higher mass sideband contribution.

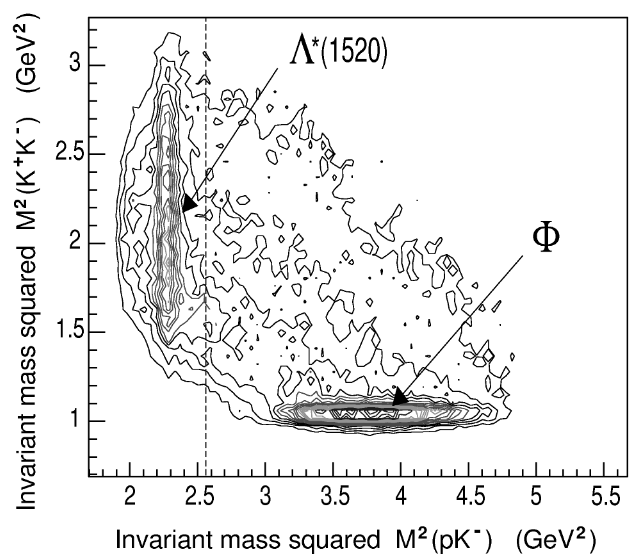

FIG. 4. Invariant mass squared $M^2(K^+K^-)$ as a function of $M^2(pK^-)$.

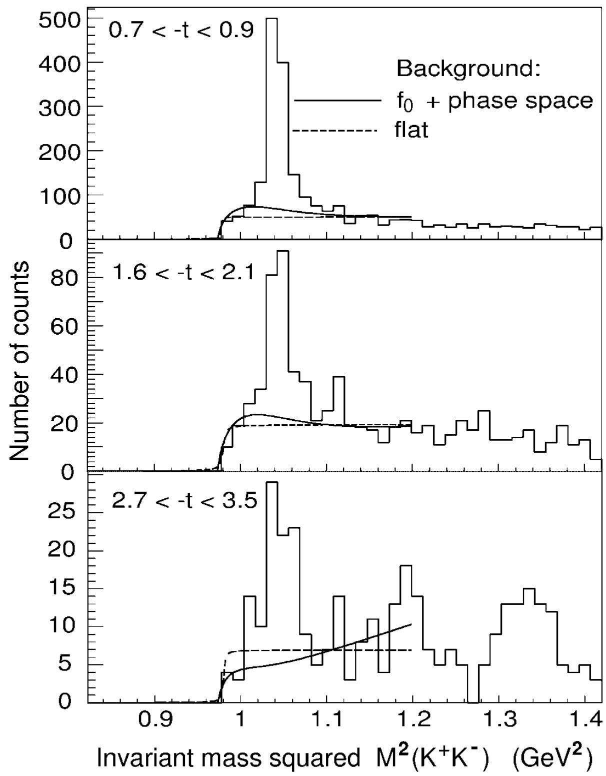

FIG. 5. Invariant mass K^+K^- for selected values of the four-momentum transfer t (GeV^2), after sideband subtraction. The curves show the continuum obtained from the fits discussed in the text.

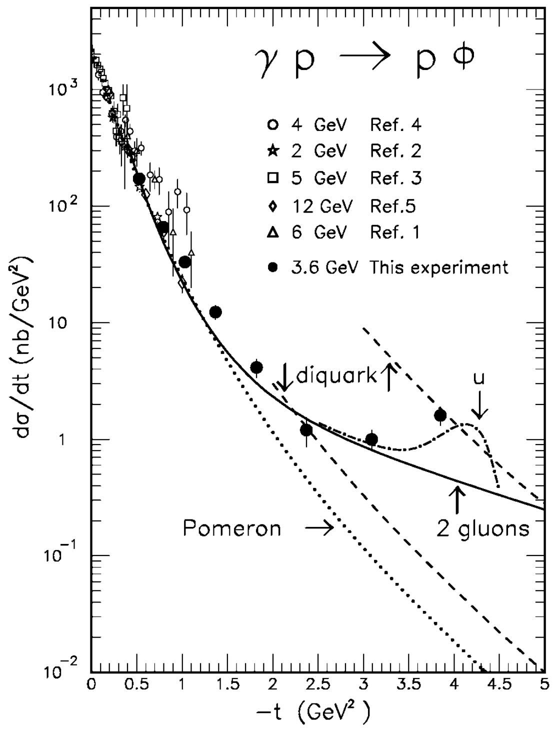

FIG. 6. The differential ϕ photoproduction cross section versus the four-momentum transfer t (see text for the explanation of the curves). The error bars displayed are the quadratic sum of statistical and systematic uncertainties which include 3% for normalization, 5% for acceptance, and 5%–15% for background subtraction.

corresponds to the exchange of two nonperturbatively dressed gluons [10,11] that may couple to any quark in the ϕ meson and in the proton. It includes quark correlations in the proton, assuming the simplest form of its wave function [18]: three valence quarks equally sharing the proton longitudinal momentum. The parameters in this model are fixed by the analysis of other independent channels. It also reproduces the data recently recorded at HERA [19] up to $-t = 1\ \mathrm{GeV}^2$ (see Ref. [11]).

The solid curve gives a good qualitative description of the experiment over the entire range of t except for the last point at $-t = 3.9\ \mathrm{GeV}^2$. Here, one approaches the kinematical limit and u-channel nucleon exchange may contribute [11]. Performing the experiment at higher average energy (4.5 GeV) would push the u-channel contribution to higher values of $|t|$ ($6\ \mathrm{GeV}^2$) and leave a wider window to study two-gluon exchange mechanisms.

The dot-dashed curve includes the u-channel contribution with the choice $g_{\phi NN} = 3$ for the ϕNN coupling (the addition of the u-channel amplitude to the dominant t-channel amplitude does not lead to double counting, because the former relies on quark exchange and the latter relies on gluon exchange). This value comes from the analysis of nucleon electromagnetic form factors [20] as well as nucleon-nucleon and hyperon-nucleon scattering [21]. It is higher than the value $g_{\phi NN} = 1$ predicted from SU(3) mass splitting or $\omega - \phi$ mixing [22], thus confirming evidence for additional Okubo-Zweig-Iizura–evading processes at the ϕNN vertex.

The predictions of two other models are also presented in Fig. 6. Both treat the gluon exchange in perturbative QCD (this leads to the steep t behavior) and use a diquark model to take into account quark correlations in the proton (this fixes the magnitude of the cross section). Berger and Schweiger [12] (upper dashed curve) use a wave function which leads to a good accounting of Compton scattering and nucleon form factors, while Carimalo *et al.* [13] (lower dashed curve) use a wave function which fits the cross section of the $\gamma\gamma \to p\bar{p}$ reaction. Above $-t = 2\ \mathrm{GeV}^2$ our data rule out the t dependence of these diquark models, demonstrating that the asymptotic regime is not yet reached in the ϕ production channel, and that the use of nonperturbatively dressed gluon exchange is better suited to this kinematics range. Recently, a new anomalous Regge trajectory associated with the $f_1(1285)$ meson has been proposed [23]. It reproduces the HERA [19] data ($-t < 1\ \mathrm{GeV}^2$), but its momentum dependence is too steep to reproduce our high t data.

The ϕ decay angular distribution will be published later. Up to $-t \sim 2.5\ \mathrm{GeV}^2$, it follows a $\sin^2\theta_{K^+}^{\mathrm{cm}}$ dependence, in agreement with s-channel helicity conservation (SCHC): a real photon produces a ϕ meson with only transverse components [24]. Above, where the u-channel contributes, a slight violation of SCHC is observed.

In conclusion, elastic photoproduction of ϕ mesons from the proton was measured for the first time up to $-t = 4$ GeV^2. Below $-t \approx 1$ GeV^2, our data cannot distinguish between the Pomeron exchange and the two-gluon exchange models. At high t, the predictions of these models differ by more than an order of magnitude. Above $-t \approx 1.8$ GeV^2, our data rule out the diffractive Pomeron and strongly favor its two-gluon realization. Not only does this finding open a window to the study of the quark correlation function in the proton, but also it provides us with a new insight on our understanding of the meson-nucleon interaction at short range. It fixes the size of the two-gluon exchange part, and the comparisons with the ρ meson photoproduction data, which have been taken concurrently, will tell us the relative importance of the quark interchange mechanisms. Such analysis is in progress and will be reported later.

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