Kaon production via $\gamma N \rightarrow K\Sigma$ in the chiral quark model

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In this paper, we present a calculation of the four isospin channels of the kaon photoproduction $\gamma N \rightarrow K\Sigma$ in the framework of the chiral quark model. The relative strength and phases in each isospin channel are determined by the quark model wave function with SU(6)⊗O(3) symmetry. The duality hypothesis is imposed to limit the number of the t channel exchanges. The only free parameter, the coupling constant $g_{K\Sigma N}$, is fitted to the total cross section data in $\gamma p \rightarrow K^+\Sigma^0$ channel. We found a remarkable agreement with the data available in the other isospin channels, and it represents a dramatic improvement over the similar calculation in the traditional isobaric model. [S0556-2813(96)51611-0]

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The meson photoproductions of nucleons play a very important role in the experimental program at the newly constructed electron facilities, such as CEBAF, ELSA, and MAMI. More systematic data in π, η, and K photoproductions from these facilities provide us a golden opportunity to study the structure of baryon resonances, and a better understanding of the reaction mechanism in terms of quantum chromodynamics (QCD) has become increasingly important. There has been considerable progress during the past year in establishing the connection between the reaction mechanism and the QCD. A new framework has been developed for the meson, in particular π, η, and K, photoproductions in the chiral quark model, in which the quark and gluon degrees of freedom are introduced explicitly. It begins with the low-energy QCD Lagrangian, in which π, η, and K are treated as Goldstone bosons and their interactions with the quarks inside hadrons are invariant under the chiral transformation. Our early investigations showed that the model-independent low-energy theorem in the threshold pion photoproduction is recovered [1] explicitly, and the initial results in the K [2] and η [3] photoproductions of nucleons in the chiral quark model have produced very good agreements between the theory and the experimental data with far less parameters.

The reaction $\gamma N \rightarrow K\Sigma$ is particularly interesting since it involves four isospin channels that include the charge and neutral kaon productions from both proton and neutron targets. Because the relative strength and phases of s-, u-, and t-channel resonances in these reactions are determined by the quark model wave functions, it would be an important test to this approach if the model gives a good description of these reactions with the same set of parameters. A similar calculation has also been done by Mart *et al.* [4] in the traditional isobaric models, and it was found that the calculated cross sections for $\gamma p \rightarrow K^0\Sigma^+$ are at least 10 times larger than the data suggested if the same set of the parameters in the $\gamma p \rightarrow K^+\Sigma^0$ channel are used. In this Rapid Communication, we present a chiral quark model calculation of the reaction $\gamma N \rightarrow K\Sigma$ with only one free parameter, the coupling constant $g_{K\Sigma N}/\sqrt{4\pi}$, and the parameters that are well determined in the quark model. The results show a remarkable overall agreement with the data in both differential and total cross sections.

We shall discuss briefly the chiral quark model approach to the meson photoproductions of the nucleon, as the detailed formalism in the quark model has been given in Refs. [2] and [3]. There are four components for the photoproductions of the pseudoscalar mesons based on the low-energy QCD Lagrangian in Ref. [5]; the contact term and the s-, u-, and t-channel contributions, thus the matrix element for the meson photoproductions can be written as

$$\mathcal{M}_{if} = \mathcal{M}_c + \mathcal{M}_t + \mathcal{M}_s + \mathcal{M}_u . \tag{1}$$

The contact term $\mathcal{M}_c$ in Eq. (1) is generated by the gauge transformations of the axial vector in the QCD Lagrangian. It is proportional to the charge of the outgoing mesons, therefore, it does not contribute to the productions of the charge neutral mesons, such as the K^0 productions in the reactions $\gamma N \rightarrow K\Sigma$. Moreover, the integrations of the spatial wave functions of the initial and final baryons generate a form factor that has a maximum value at the forward angle and decreases as the scattering angle between the incoming photon and the outgoing meson increases. This leads to an interesting prediction from the quark model; the charged meson productions should be forward peaked above the threshold because of the dominance of the contact term in the low-energy region. The data in charged kaon and the neutral η productions are quite consistent with this conclusion. The second term $\mathcal{M}_t$ in Eq. (1) is the t-channel K^+ exchange, and it is proportional to the charge of the outgoing mesons as well. This term is required so that the total transition amplitude in Eq. (1) is gauge invariant. The other t-channel exchanges, such as the K^* and $K1$ exchanges in the kaon productions, which played an important role in Ref. [6], are excluded with the input of the duality hypothesis [7,8]. This was not imposed in our early investigation [2] of the kaon photoproductions, in which the K^* exchange was included.

The u-channel contributions $\mathcal{M}_u$ in Eq. (1) include Σ $(\Lambda+\Sigma^0)$ exchanges for the $\Sigma^{\pm}(\Sigma^0)$ final states, the Σ^* exchanges and the excited hyperon exchanges, of which the formulas have been given in Ref. [2]. The excited hyperons in this framework are treated as degenerate so that their total contributions can be written in a compact form in the quark model. This is a good approximation since the contributions from the u-channels resonances are not sensitive to their precise mass positions. There are two parts in the s-channel contributions $\mathcal{M}_s$ in Eq. (1): the s-channel resonances below 2 GeV and those above 2 GeV that could be regarded as continuum contributions. The electromagnetic transitions of the s-channel baryon resonances and their meson decays have been investigated extensively in the quark model [9–12] in terms of the helicity and the meson decay amplitudes. These transition amplitudes for s-channel resonances below 2 GeV have been translated into the standard CGLN [13] amplitudes in Refs. [2,3] for the proton target and [14] for the neutron target in the harmonic oscillator basis. The advantage of the standard CGLN variables is that the kinematics of the meson photoproductions has been thoroughly investigated [15], the various observables of the meson photoproductions could be easily evaluated in terms of these amplitudes. Those resonances above 2 GeV are treated as degenerate, since little experimental information is available on those resonances. Qualitatively, we find that the resonances with higher partial waves have the largest contributions as the energy increases. Thus, we write the total contributions from the resonances belonging to the same harmonic oscillator shell in a compact form, and the mass and total width of the high spin states, such as $G_{17}(2190)$ for $n=3$ harmonic oscillator shell, are used.

We assume that the relative strength and phases of each term in s, u, and t channels are determined by the quark model wave function with exact SU(6)⊗O(3) limit. The masses and decay widths of the s-channel baryon resonances are obtained from the recent Particle Data Group [16]. Thus, there are four parameters in this calculation: the coupling constant $g_{KN\Sigma}$, the constituent quark masses m_q for up or down quarks and the strange quarks, and the parameter α^2 from the harmonic oscillator wave functions in the quark model. The coupling constant $g_{KN\Lambda}$ in the u-channel Λ exchange term for the processes with Σ^0 final states is related to the coupling constant $g_{KN\Sigma}$ by $g_{KN\Sigma}=-(1/\sqrt{3})\,g_{KN\Lambda}$ in the SU(3) symmetry. The quark masses m_q and the parameter α^2 are well determined in the quark model. They are

$$m_u=m_d=0.34 \text{ GeV}$$

$$m_s=0.55 \text{ GeV}$$

$$\alpha^2=0.16 \text{ GeV}^2. \qquad (2)$$

In principle, the coupling constant $g_{KN\Sigma}$ can also be determined in the chiral quark model via a generalized Goldberger-Treiman relation [17]. However, the theoretical uncertainty for the kaon coupling constant is quite large compared to the pion coupling case due to the large quark mass effects [18]. Thus, the coupling constant $g_{KN\Sigma}/\sqrt{4\pi}$ is treated as a free parameter at this stage, and is to be determined in our calculation.

In Fig. 1, we show the calculated total cross sections for all four channels in $\gamma N\rightarrow K\Sigma$. The parameter $g_{KN\Sigma}/\sqrt{4\pi}$ is 1.55 from the fits to the total cross sections in the $\gamma p\rightarrow K^+\Sigma^0$ channel, which is not inconsistent with that obtained from the kaon-nucleon scattering [19]. There are several interesting features that highlight the dynamical roles by

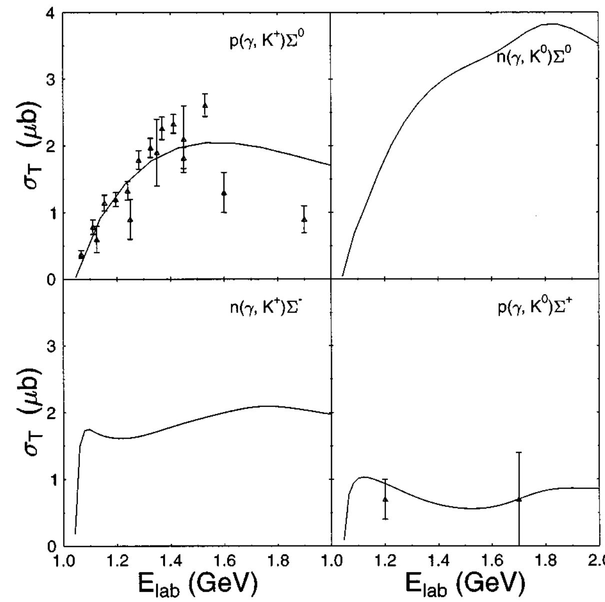

FIG. 1. The total cross sections for the four isospin channels, $\gamma N\rightarrow K\Sigma$. The experimental data are from Ref. [24].

the s-channel resonances in the quark model. A common feature for all four isospin channels is the dominance of the resonances with isospin 3/2, especially those belonging to **56** multiplet in the quark model. There are four such resonances whose masses are around 1.95 GeV, and they are $F_{37}(1950)$, $F_{35}(1905)$, $P_{33}(1920)$, and $P_{31}(1910)$. The dominance of these resonances leads to the maximum in total cross sections around 1.5 GeV in $\gamma p\rightarrow K^+\Sigma^0$, and a minimum around 1.5 GeV in $\gamma p\rightarrow K^0\Sigma^+$ channel because of a relative -1 phase between the charge and neutral kaon productions for the proton target in the quark model. This seems to be consistent with the data. Another important feature is that the resonances $S_{11}(1650)$ and $D_{15}(1670)$ play a very important role in the kaon productions for the neutron target, while they give no contribution to the kaon productions for the proton target. In the quark model, these resonances belong to the SU(6) multiplet $N(^4P_M)$, and their electromagnetic transitions to the protons vanish due to the Moorhouse selection rule [20]. The scattering cross sections are particularly sensitive to the presence of the resonance $S_{11}(1650)$ in the threshold region, as its mass is just below the threshold energy for the $K\Sigma$ final states. The peak at threshold in the $\gamma n\rightarrow K^+\Sigma^-$ would disappear if the contributions from this resonance are removed.

We find a strong correlation between the relative strength of the S_{11} resonances and the coupling constant $g_{KN\Sigma}/\sqrt{4\pi}$, as the masses of these S_{11} resonances are around the threshold of the kaon productions. However, the structure of two S_{11} resonances, $S_{11}(1535)$ and $S_{11}(1650)$, has not been understood theoretically, which has been a major source of uncertainties in determining the coupling constant $g_{KN\Sigma}/\sqrt{4\pi}$. The recent analysis [21] suggests that the branching ratio of the resonance $S_{11}(1535)$ decaying into ηN is larger than that predicted in the quark model, while branching ratio $\Gamma_{\pi N}/\Gamma$ for the resonance $S_{11}(1650)$ is approaching unity [22], making it the most elastic resonance apart from the $P_{11}(1232)$. One of the solutions of this puzzle is the possible existence of a third S_{11} resonance with a mass 1.72 GeV [21], which suggests a quasibound $K\Lambda$ or $K\Sigma$ state in the wave functions of S_{11} resonances. Because the mass of this S_{11} resonance is just above the threshold of the kaon production, it could play the same role in the $K\Sigma$ production as the resonance $S_{11}(1535)$ in the η photoproduction, although the relative strength may not be that strong. Thus, the reaction $\gamma N \to K\Sigma$ would be a potentially important channel to confirm the presence of the third S_{11} resonance in nature. Incorporating this resonance is beyond the quark model, and requires more elaborate modeling and more precise data, which remains to be investigated.

The overall agreement with the few available data in $\gamma p \to K^+\Sigma^0$ and $\gamma p \to K^0\Sigma^+$ channels is indeed very encouraging, considering that only one parameter is being fitted to the data for all four channels. It represents a dramatic improvement over the similar calculations in Ref. [4]. This shows that the quark model wave functions indeed provide the correct relative strength and phases among the terms in the s, u, and t channels. Moreover, we find that the overall agreement with the available data in the differential cross sections is quite satisfactory as well. The results in differential cross sections for the reaction $\gamma N \to K\Sigma$ are shown in Fig. 2 at $E_{\mathrm{lab}} = 1.45$ GeV. The behavior of the differential cross section in the reactions $\gamma N \to K\Sigma$ are dominantly determined by the contact term and the resonances with the isospin 3/2. The form factor in the contact term $\mathcal{M}_c$ generates the forward peaking behavior, while the isospin 3/2 resonances, such as the resonances $F_{37}(1950)$, $F_{35}(1905)$, $P_{33}(1920)$, and $P_{31}(1910)$ that are produced by the magnetic multipole transitions in the quark model, lead to the differential cross sections that are peaked around scattering angle 90°. Thus, the differential cross sections for the charged kaon productions, $\gamma p \to K^+\Sigma^0$ and $\gamma n \to K^+\Sigma^-$, are forward peaked, while those for the neutral kaon productions, $\gamma p \to K^0\Sigma^+$ and $\gamma n \to K^0\Sigma^0$, are slightly backward peaked, because the contact term is proportional the charge of the outgoing meson. On the other hand, the differential cross-section data for the reaction $\gamma p \to K^+\Lambda$ show a straightforward peaking behavior, in which the isospin 3/2 resonances do not contribute. This is consistent with the quark model predictions. It is also interesting to note that the total cross section in $\gamma p \to K^0\Sigma^+$ has a minimum around $E_{\mathrm{lab}} = 1.5-1.6$ GeV, and the corresponding differential cross section also has a minimum around 90°. Both minima reflect

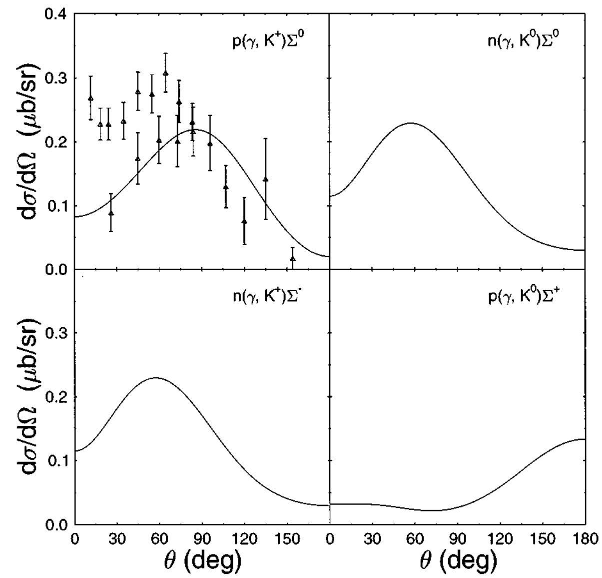

FIG. 2. The differential cross sections at $E_{\mathrm{lab}} = 1.45$ GeV for the four isospin channels of $\gamma N \to K\Sigma$. The experimental data come from Ref. [24], and they have a $\mu b/sr$ unit.

the negative contributions from the resonances $F_{37}(1950)$, $F_{35}(1905)$, $P_{33}(1920)$, and $P_{31}(1910)$. The experiments at CEBAF [23] in the near future will certainly provide an important test to these predictions.

Of course, we do not expect that the naive quark model in the pure symmetry limit gives a quantitative description of this reaction. It does provide a good framework to perform a quantitative analysis of the kaon photoproductions, in which both reactions, $\gamma N \to K\Lambda$ and $\gamma N \to K\Sigma$, can be studied simultaneously. It also highlights the dynamic roles by the s-channel resonances, such as the resonances with the isospin 3/2, and S_{11} resonances. More systematic evaluations of the experimental observables including both cross sections and polarizations for all isospin channels are in progress, and the result will be published elsewhere.

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