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The role of vector-baryon channels and resonances in the $\gamma p \to K^0\Sigma^+$ and $\gamma n \to K^0\Sigma^0$ reactions near the $K^*\Lambda$ threshold

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ABSTRACT

We have studied the $\gamma p \to K^0\Sigma^+$ reaction in the energy region around the $K^*\Lambda$ and $K^*\Sigma$ thresholds, where the CBELSA/TAPS cross section shows a sudden drop and the differential cross section experiences a transition from a forward-peaked distribution to a flat one. Our coupled-channel model incorporates the dynamics of the vector meson–baryon interaction which is obtained from the hidden gauge formalism. We find that the cross section in this energy region results from a delicate interference between amplitudes having $K^*\Lambda$ and $K^*\Sigma$ intermediate states. The sharp downfall is dictated by the presence of a nearby N^* resonance produced by our model, a feature that we have employed to predict its properties. We also show results for the complementary $\gamma n \to K^0\Sigma^0$ reaction, the measurement of which would test the mechanism proposed in this work.

1. Introduction

The recent work reported by the CBELSA/TAPS Collaboration [1] puts a challenge to the ordinary models of photoproduction of mesons. The reaction is $\gamma p \to K^0\Sigma^+$, which exhibits a peak in the cross section around $\sqrt{s} = 1900$ MeV followed by a fast downfall around $\sqrt{s} = 2000$ MeV. Most remarkable, the differential cross section is flat close to threshold, becomes forward peaked close to the energy where the cross section has a maximum but, up to the resolution of the experiment, appears again isotropic in the region where the total cross section is small and nearly constant, from $\sqrt{s} = 2000$ MeV to $\sqrt{s} = 2200$ MeV. The experiment complements and improves earlier measurements of Crystal Barrel [2] and SAPHIR [3]. As shown in [1], sophisticated models of K photoproduction like K-MAID [4] and SAID [5] grossly fail to reproduce the experimental features, even when changes are made to adapt the models to this particular reaction. The same fate is shown to follow for the models [6–8], as discussed in [3].

In this work we present a theoretical approach that gives an explanation to the features observed in the $\gamma p \to K^0\Sigma^+$ reaction around $\sqrt{s} = 2000$ MeV. The experimental paper [1] hints to some mechanisms involving vector meson–baryon channels, since the prominent feature discussed above occurs in between the $K^*\Lambda$ and $K^*\Sigma$ thresholds, at 2010 MeV and 2087 MeV, respectively. Our model implements the vector-baryon interaction for vectors of the nonet with the octet of baryons obtained in [9], using the local hidden gauge Lagrangians [10–12] and coupled channels in an unitary approach. This vector-baryon interaction leads to the dynamical generation of $1/2^-$ and $3/2^-$ resonances, degenerate in spin–parity, one of which appears around 1970 MeV and couples to ρN, ωN, ϕN but mostly to $K^*\Lambda$ and $K^*\Sigma$. The fact that this resonance appears close to the location of the downfall of the cross section suggests that any realistic theoretical scheme trying to reproduce this problem should consider the explicit incorporation of these channels and their interaction, as done in the present work. We show that the interference of the $K^*\Lambda$ and $K^*\Sigma$ channels, magnified by the presence of the resonance, is essential for reproducing the behavior of the $\gamma p \to K^0\Sigma^+$ cross section around 2000 MeV. We also give predictions for the $\gamma n \to K^0\Sigma^0$ reaction, which has a quite different interference pattern and shows a peak in the energy region where the $\gamma p \to K^0\Sigma^+$ has the downfall. A measurement of the neutral reaction could then bring further light into the physics hidden in these processes.

2. Formalism

The hidden gauge approach incorporates automatically vector-meson dominance [13], converting the photon into a vector meson, which later on interacts with the other hadrons. Our basic mechanisms for the $\gamma N \to K^*\Sigma$ reaction are depicted in Fig. 1, where we can see the photon conversion into ρ^0, ω, ϕ, followed by the $\rho N, \omega N, \phi N$ interaction leading to the relevant vector-baryon

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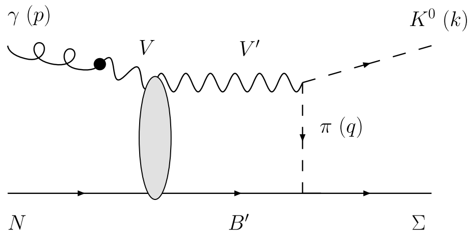

Fig. 1. Mechanism for the photoproduction reaction $\gamma N \to K^0\Sigma$. The symbol V stands for the ρ^0, ω and ϕ mesons, while $V'B'$ denotes the intermediate channel, which can be $K^{*+}\Lambda$, $K^{*+}\Sigma^0$ or $K^{*0}\Sigma^+$, in the case of $\gamma p \to K^0\Sigma^+$, and $K^{*+}\Sigma^-$ or $K^{*0}\Lambda$, in the case of $\gamma n \to K^0\Sigma^0$, the $K^{*0}\Sigma^0$ one not contributing in the later reaction due to the zero value of the $\pi^0\Sigma^0\Sigma^0$ coupling at the Yukawa vertex.

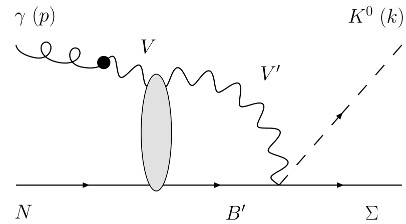

Fig. 2. Kroll–Ruderman contact term to be added to the mechanisms of Fig. 1 to preserve gauge-invariance in the photoproduction reactions $\gamma N \to K^0\Sigma$.

($V'B'$) channels, which are of $K^*\Lambda$ or $K^*\Sigma$ type, since those are the ones to which the resonance around 1970 MeV couples most strongly according to the model of Ref. [9]. Finally, the intermediate $K^*\Lambda$ or $K^*\Sigma$ states get converted via pion exchange to the final $K^0\Sigma^+$, in the case of γp, or $K^0\Sigma^0$, in the case of γn. We take the vector-baryon amplitudes $VN \to V'B'$ from the work of Ref. [9]. Since in the final state we have a pseudoscalar meson and a baryon, it would be most appropriate to work with a model space that contains both the pseudoscalar-baryon and the vector-baryon channels, as done in [14–16]. Yet, at the energy that we are concerned we can neglect the interaction of the pseudoscalar-baryon channels since they do not produce any resonance around this region [17], and then consider just the interaction of the vector-baryon channels plus the mechanism responsible for the transition from the vector-baryon intermediate states to the final pseudoscalar-baryon state that we take from [14]. The formalism of Ref. [9] was developed under the assumption that the momenta of the external mesons was small. In the present work, the momentum of the photon and, hence, that of the virtual ρ^0, ω or ϕ mesons, is not small, but some of the simplifying assumptions of the model of Ref. [9] are still valid or have a limited influence. On the one hand, neglecting the zeroth component of the polarization vector, ϵ^0, is still possible for these mesons since they acquire the polarization vector of the photon, which is of transverse nature. On the other hand, we have estimated that the size of the linear momentum terms neglected here to be about 15% of the dominant contributions to the $VB \to V'B'$ interaction. This observation can justify a posteriori why the small three-momentum approximation applied in the radiative decays of vector–vector molecules [18–20] led to such good results in spite of the finite momentum of the emitted photons. Further details on the interaction of vectors with mesons and baryons can be seen in the review [21] and in Ref. [22].

The photon–vector conversion Lagrangian is given by

$$\mathcal{L}_{\gamma V} = -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle, \tag{1}$$

with $Q = \mathrm{diag}(2, -1, -1)/3$ and A_μ being the photon field. The charge of the electron, e, is negative and normalized as $e^2/4\pi = 1/137$.

The $V'PP$ vertex is obtained from

$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\mu P] V^\mu \rangle, \tag{2}$$

with the coupling of the theory given by $g = \frac{M_V}{2f}$ where $f =$ 93 MeV is the pion decay constant and M_V the vector-meson mass. The magnitude V_μ is the SU(3) matrix of the vectors of the ρ nonet and P stands for the matrix of the pseudoscalar mesons of the π.

Finally, the Yukawa vertex is described by the Lagrangian:

$$\mathcal{L}_{PBB} = \frac{1}{2}(D+F)\langle \bar{B}\gamma^\mu\gamma^5 u_\mu B \rangle + \frac{1}{2}(D-F)\langle \bar{B}\gamma^\mu\gamma^5 B u_\mu \rangle, \tag{3}$$

where the term $\gamma^\mu\gamma^5 u_\mu$ is taken in its non-relativistic form:

$$\gamma^\mu\gamma^5 u_\mu \to \frac{\sqrt{2}}{f}\sigma^i \partial_i \phi, \quad i = 1, 2, 3, \tag{4}$$

B is the matrix representing the baryon octet, and $D = 0.795$, $F =$ 0.465 are taken from [23].

The amplitude corresponding to the mechanism in Fig. 1 is given by:

$$\begin{aligned} -it^{\pi\text{-pole}}_{\gamma N \to K^0\Sigma} = {} & e \sum_{V=\rho^0,\omega,\phi} \mathcal{C}_{\gamma V} \sum_{V'B'} t_{VN \to V'B'} \\ & \times i \int \frac{d^4q}{(2\pi)^4} \frac{1}{(q+k)^2 - M_{V'}^2 + i\varepsilon} \frac{1}{q^2 - m_\pi^2 + i\varepsilon} \\ & \times \frac{M_{B'}}{E_{B'}} \frac{1}{P^0 - q^0 - k^0 - E_{B'}(\vec{q}+\vec{k}) + i\varepsilon} \\ & \times (\vec{q}-\vec{k})\vec{\epsilon}_\gamma \vec{\sigma}\vec{q} V_{Y,B'} F(q), \end{aligned} \tag{5}$$

where

$$\mathcal{C}_{\gamma V} = \begin{cases} \frac{1}{\sqrt{2}} & \text{for } V = \rho^0, \\ \frac{1}{3\sqrt{2}} & \text{for } V = \omega, \\ -\frac{1}{3} & \text{for } V = \phi \end{cases} \tag{6}$$

and

$$V_{\Sigma^+,B'} = \begin{cases} \frac{2D}{2f\sqrt{3}} & \text{for } V'B' = K^{*+}\Lambda, \\ -\frac{2F}{2f} & \text{for } V'B' = K^{*+}\Sigma^0, \\ \frac{2F}{2f}\left(-\frac{1}{\sqrt{2}}\right) & \text{for } V'B' = K^{*0}\Sigma^+ \end{cases} \tag{7}$$

in the case of $\gamma p \to K^0\Sigma^+$, while

$$V_{\Sigma^0,B'} = \begin{cases} \frac{2F}{2f} & \text{for } V'B' = K^{*+}\Sigma^-, \\ \frac{2D}{2f\sqrt{3}}\left(-\frac{1}{\sqrt{2}}\right) & \text{for } V'B' = K^{*0}\Lambda \end{cases} \tag{8}$$

in the case of $\gamma n \to K^0\Sigma^0$. Note that the factor $-1/\sqrt{2}$ appearing in $V_{Y,B'}$ when $V' = K^{*0}$ accounts for the relation between the neutral meson coupling, $K^{*0} \to \pi^0 K^0$, to the charged meson one, $K^{*+} \to \pi^+ K^0$, in the $V'PP$ vertex. For the form factor $F(q)$ we take a typical Yukawa static shape, $\Lambda^2/(\Lambda^2 + \vec{q}^2)$ with a cut-off $\Lambda = 850$ MeV, a value that has been adjusted to reproduce the size of the experimental $\gamma p \to K^0\Sigma^+$ cross section. One could also argue that there can be an extra form factor at the meson VPP vertex. In such a case, one should consider our prescription as an empirical way of accounting for these combined finite-size effects.

In order to implement gauge invariance, the amplitudes of Eq. (5) must be complemented by the corresponding Kroll–Ruderman contact term [14–16], displayed in Fig. 2 and given by