VECTOR-BARYON DYNAMICS IN $\gamma N \rightarrow K^0 \Sigma$ REACTIONS*

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A coupled channel model for the interaction of vector mesons with baryons is employed in the study of the $\gamma p \rightarrow K^0 \Sigma^+$ reaction around the $K^* \Lambda$ and $K^* \Sigma$ thresholds, where the recent 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. A delicate interference between amplitudes having $K^* \Lambda$ and $K^* \Sigma$ intermediate states is found. The sharp downfall is dictated by the presence of a N^* resonance produced by our model, a feature that we have employed to infer its properties. Predictions for the complementary $\gamma n \rightarrow K^0 \Sigma^0$ reaction are also given.

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1. Introduction

The use of effective Lagrangians combined with unitarizing techniques has proven to be a very efficient tool to understand a variety of problems in hadron physics. One of the most emblematic examples is the description of the $\Lambda(1405)$ as the superposition of two nearby poles of the unitarized pseudoscalar-baryon scattering amplitude,¹⁻⁵ a fact that has found experimental support as reported in.^{6,7}

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The description of baryon production reactions covering the region of energy around 2 GeV, requires an extension of these models to incorporate also the interaction of vector mesons with baryons. A powerful tool is provided by the hidden gauge formalism,^{8–10} applied recently to generate resonances as vector-baryon quasibound states^{11,12} and allowing the simultaneous coupling to pseudoscalar-baryon states.^{13,14} Alternatively, one may employ flavour-spin SU(6) symmetric models.^{15,16}

We present the results of a theoretical approach for the $\gamma p \rightarrow K^0 \Sigma^+$ reaction, recently measured by the CBELSA/TAPS collaboration,¹⁷ which complements and improves earlier measurements of Crystal Barrel¹⁸ and SAPHIR.¹⁹ The total cross section shows a sudden drop at $\sqrt{s} = 2000$ MeV and the differential cross section experiences a transition from a forward-peaked distribution to a flat one. As shown in,¹⁷ sophisticated models of K photoproduction like K-MAID²⁰ and SAID²¹ grossly fail to reproduce these 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,^{22–24} as discussed in.¹⁹ In this work we show that the explicit consideration of vector mesons and their unitarized interaction with baryons are crucial ingredients to understand the behavior of the $\gamma p \rightarrow K^0 \Sigma^+$ cross section around 2000 MeV.

2. Formalism

Our basic mechanisms for the $\gamma N \rightarrow K^0 \Sigma$ reaction are depicted in Figs. 1 and 2, where we can see the photon conversion into $V = \rho^0, \omega, \phi$, followed by the $\rho N, \omega N, \phi N$ interaction leading to the relevant vector-baryon ($V'B'$) channels. The vector-baryon amplitudes $VN \rightarrow V'B'$ are taken from the work of Ref.,¹² which show degenerate $1/2^-$ and $3/2^-$ baryon poles around 1970 MeV, coupling mostly to $K^* \Lambda$ or $K^* \Sigma$, being those the only intermediate $V'B'$ states that we consider in this work. Finally, the $K^* \Lambda$ or $K^* \Sigma$ states get converted via pion exchange to the final $K^0 \Sigma$ state. Note that, since the final meson is a neutral one, the tree-level t-channel and Kroll-Rudermann diagrams are zero. Together with the fact that the s-channel and u-channel terms are small, this enhances the role of loops in the $\gamma N \rightarrow K^0 \Sigma$ reaction, which becomes particularly sensitive to coupled channel effects.

Applying field diagrammatic techniques and taking the needed Lagrangians from the hidden gauge formalism, one finds:

$$-it_{\gamma N \rightarrow K^0 \Sigma} = A \vec{\sigma} \vec{k} \vec{\epsilon}_\gamma \vec{k} + B \vec{\sigma} \vec{\epsilon}_\gamma, \quad (1)$$

where

$$A = e \sum_{V=\rho^0, \omega, \phi} \mathcal{C}_{\gamma V} \sum_{V'B'} t_{VN \rightarrow V'B'} V_{Y,B'} \tilde{G}_{V'B'}^{(1)}, \quad (2)$$

and

$$B = e \sum_{V=\rho^0, \omega, \phi} \mathcal{C}_{\gamma V} \sum_{V'B'} t_{VN \rightarrow V'B'} V_{Y,B'} \left(\tilde{G}_{V'B'}^{(2)} + G_{V'B'} \right). \quad (3)$$

Fig. 1. Mechanism for the photoproduction reaction $\gamma N \rightarrow K^0 \Sigma$. 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 $\gamma p \rightarrow K^0 \Sigma^+$, and $K^{*+}\Sigma^-$ or $K^{*0}\Lambda$, in the case of $\gamma n \rightarrow K^0 \Sigma^0$, the $K^{*0}\Sigma^0$ one not contributing 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 $\gamma N \rightarrow K^0 \Sigma$.

Further details of the calculation and the explicit expressions for the couplings $\mathcal{C}_{\gamma V}$, $V_{Y,B'}$, and the loop functions $\tilde{G}_{V'B'}^{(1)}$, $\tilde{G}_{V'B'}^{(2)}$ and $G_{V'B'}$ can be found in Ref.²⁵ The cross section reads:

$$\frac{d\sigma_{\gamma N \rightarrow K^0 \Sigma}}{d\Omega} = \frac{1}{16\pi^2} \frac{M_N M_\Sigma}{s} \frac{k}{p} \overline{\sum} \sum |t_{\gamma N \rightarrow K^0 \Sigma}|^2, \quad (4)$$

where

$$\overline{\sum} \sum |t_{\gamma N \rightarrow K^0 \Sigma}|^2 = \frac{1}{2} \left\{ \left[|A|^2 \vec{k}^2 + 2 \operatorname{Re}(AB^*) \right] \vec{k}^2 \sin^2 \theta + 2 |B|^2 \right\}. \quad (5)$$

3. Results

The importance of coupled channels was pointed out recently²⁶ to understand the differences in the neutral η meson production reactions $\gamma p \rightarrow \eta p$ and $\gamma n \rightarrow \eta n$ around the energy region of the $K\Lambda, K\Sigma$ thresholds. A destructive interference between intermediate $K^+\Lambda$ and $K^+\Sigma^0$ states was found in the $\gamma p \rightarrow \eta p$ reaction, which was absent in the $\gamma n \rightarrow \eta n$ one due to the only presence of the $K^+\Sigma^-$ state. An analogous situation is found here, since the photon couples to both the $K^{*+}\Lambda$ and the $K^{*+}\Sigma^0$ states in the $\gamma p \rightarrow K^0 \Sigma^+$ process, while it only couples to the $K^{*+}\Sigma^-$ state in the $\gamma n \rightarrow K^0 \Sigma^0$ one. However, the analysis is slightly more involved in the present work because of the additional π -exchange mechanism (or contact interaction) leading to the final $K^0 \Sigma$ state, which makes the neutral $K^{*0}Y$ states to also play an explicit role in the additional intermediate loop function.

In Fig. 3 we see how the consideration of the different intermediate channels, $K^*\Sigma$ (dashed lines) and $K^*\Lambda$ (dotted lines), build up the final cross section (solid lines), in the case of the $\gamma p \rightarrow K^0 \Sigma^+$ (upper panel) and $\gamma n \rightarrow K^0 \Sigma^0$ (lower panel) reactions. The destructive interference between the $K^*\Sigma$ and $K^*\Lambda$ amplitudes, of similar size and shape in the case of the $\gamma p \rightarrow K^0 \Sigma^+$ reaction, produce an abrupt downfall of the cross section, right at the position of the resonance generated by our VB interaction model. In contrast, the $\gamma n \rightarrow K^0 \Sigma^0$ cross section retains the peak at the position of the resonance.

Fig. 3. Contributions to the $\gamma p \rightarrow K^0 \Sigma^+$ (upper panel) and $\gamma n \rightarrow K^0 \Sigma^0$ (lower panel) cross sections.

Fig. 4. Comparison of the $\gamma p \rightarrow K^0 \Sigma^+$ cross section, obtained with two parameter sets, with the CBELSA/TAPS data of Ref.¹⁷ (upper panel). Predictions for the $\gamma n \rightarrow K^0 \Sigma^0$ cross section using two parameter sets (lower panel).

The calculated cross section for the $\gamma p \rightarrow K^0 \Sigma^+$ reaction (solid line) is compared with the experimental data¹⁷ in the upper panel of Fig. 4. The downfall of the theoretical results displayed by the solid line appears 60 MeV below the energy at which the experimental cross section presents the abrupt drop. Since this downfall is sensitive to the position of the resonance produced in this energy region, we can adjust the parameters of our model to reproduce the CBELSA/TAPS data and obtain in this way a prediction of its properties. The dashed line in Fig. 4 is obtained by changing the loop regularizing subtraction constants from a value of -2 at a regularization scale of $\mu = 630$ MeV to a value of -1.65 (except $a_{\rho N}$ which is kept at its original value of -2). Accordingly, the resonance, which in the original model¹² was found at $M_R = 1972$ MeV with a width of $\Gamma_R = 64$ MeV, moves up in energy by 60 MeV, lying then above the $K^* \Lambda$ threshold to which it couples substantially and, consequently, becoming almost twice wider. It is interesting to note that two resonances of negative parity around this region of energy, $N^*(2080)(3/2^-)$ and $N^*(2090)(1/2^-)$, which appeared in earlier versions of the PDG, have been eliminated in the latest version.²⁷ Experimental support for a $(3/2^-)$ resonance around 2080 MeV has also been found recently from an analysis of SPring 8 LEPS data on the $\gamma p \rightarrow K^+ \Lambda(1520)$ reaction in.²⁸ Our results provide another solid backing for the existence of an odd parity resonance around this energy region. Our model

Table 1. Ratio of the difference over the sum of the calculated $\gamma p \rightarrow K^0 \Sigma^+$ cross section at 0° and 90° .

W (MeV)	1823	1874	1923	1971	2018	2064	2109	2153	2197
$\frac{\sigma(0^\circ) - \sigma(90^\circ)}{\sigma(0^\circ) + \sigma(90^\circ)}$	0.14	0.20	0.24	0.29	0.31	0.30	0.23	0.17	0.16

could be further tested with a measurement of the neutral $\gamma n \rightarrow K^0 \Sigma^0$ cross section, a prediction of which is shown in the lower panel of Fig. 4 for the two different parameter sets.

The differential cross section of our model is symmetrical around 90° . To reproduce the forward-peaked data one would need to add P-wave contributions, that would interfere constructively at forward angles and destructively at backward ones, a task that goes beyond the scope of this exploratory work. However, we note that our coupled-channel model already builds up some angular structure with increasing energy, which becomes weaker above the energy where the cross section experiences the downfall, as can be better quantified by the ratio of the difference over the sum of the calculated cross section at 0° and 90° given in Table 1.

4. Conclusions

We have presented a theoretical study of the $\gamma p \rightarrow K^0 \Sigma^+$ reaction around $\sqrt{s} = 2000$ MeV, which incorporates the interaction between vector mesons with baryons, obtained from local hidden gauge Lagrangians and implementing unitarization in coupled channels.

Our results for the $\gamma p \rightarrow K^0 \Sigma^+$ reaction show, as the CBELSA/TAPS experimental data, a rapid drop of the cross section, which is a consequence of a delicate interference between amplitudes containing $K^* \Lambda$ and $K^* \Sigma$ intermediate states, magnified by the presence of a resonance that our model produces in this energy region. Since this structure is sensitive to the position of the resonance, we have used the CBELSA/TAPS data to fine tune the parameters of our model and obtain in this way a more realistic prediction of the resonance mass, that we now find at 2030 MeV.

A measurement of the interesting signature that this resonance leaves on the $\gamma n \rightarrow K^0 \Sigma^0$ reaction, showing a peak structure where the $\gamma p \rightarrow K^0 \Sigma^+$ reaction has a sharp downfall, would give extra support to the existence of this state and can bring further light into the physics hidden in these processes.

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