Study of the $\Sigma(1385)$ and $\Lambda(1405)$ resonances in K^+ photoproduction processes

Madeleine Soyeur[1], Matthias F.M. Lutz[2,3]

[1]Département d'Astrophysique, de Physique des Particules,
de Physique Nucléaire et de l'Instrumentation Associée,
Service de Physique Nucléaire, CEA/Saclay,
F-91191 Gif-sur-Yvette Cedex, France
[2]GSI, Planckstrasse 1, D-64291 Darmstadt, Germany
[3]Institut für Kernphysik, TU Darmstadt, D-64289 Darmstadt, Germany

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Abstract

The $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions are studied in the kinematic region where the $\pi^0\Lambda(1116)$ and $\pi\Sigma(1192)$ pairs originate dominantly from the decay of the $\Sigma(1385)$ and $\Lambda(1405)$ resonances. We consider laboratory photon energies around 2 GeV, i.e. total center of mass energies above the known resonance region. We compute the t-channel kaon-exchange contribution to these reactions using $K^-p \to \pi^0\Lambda$ and $K^-p \to \pi\Sigma$ amplitudes calculated in the framework of a chiral coupled-channel effective field theory of meson-baryon scattering. We extract from the calculated cross section the gauge-invariant double kaon pole term. We find this term to be large and likely to drive significantly the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions in the kinematics under investigation. Accurate measurements of t-distributions for these processes, in progress or planned at ELSA and at SPring-8, are needed to confirm this expectation and assess the possibility of studying antikaon-nucleon dynamics just below threshold through these reactions.

1 Introduction

Antikaon-nucleon dynamics close to threshold ($\sqrt{s^{thresh}}$=1.43 GeV) appears rather complex. The $\bar{K}N$ channel in that regime couples both to inelastic channels ($\Lambda\pi$ and $\Sigma\pi$) and to baryon resonances located below and above threshold. The baryon resonances present below threshold [$\Sigma(1385)$ and $\Lambda(1405)$] are strongly coupled to the hyperon-pion channels. The $\Sigma^0(1385)$ decays primarily into the $\pi^0\,\Lambda$ channel [$(88 \pm 2)\,\%$] and less significantly [$(12 \pm 2)\,\%$] into the $\pi\,\Sigma$ channel [1]. The $\Lambda(1405)$ decays entirely into the $\pi\,\Sigma$ channel [1]. We propose to study the $K^-p \to \pi^0\Lambda$ and $K^-p \to \pi\Sigma$ amplitudes below threshold, in the region where they are dominated by the $\Sigma(1385)$ and $\Lambda(1405)$ resonances, by isolating a specific term arising from K^- t-channel exchange in the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions induced by 2 GeV photons. This term is characterized by its analytic structure, a double pole linked to the K^- propagator $[1/(m_K^2 - t)^2]$, fulfills the requirement of gauge-invariance and seems to be important.

This work is largely motivated by a new generation of experiments in which multihadron final states can be measured exclusively. Section 2 is devoted to a brief review of these experimental projects. We describe in Section 3 the calculation of the t-channel K^--exchange contribution to the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions using the $K^-p \to \pi^0\Lambda$ and $K^-p \to \pi\Sigma$ amplitudes obtained in Ref. [2]. We extract the gauge-invariant double K^- pole contribution for both processes. A few numerical results for the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions based on the double K^- pole term are presented in Section 4. We conclude briefly in Section 5.

This talk is based on a recent paper [3] to which we refer for a more extensive account of our calculation and a broader presentation of the results.

2 Experimental studies of the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions

Very little is presently known on the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions induced by real photons in the region where the invariant mass of the $\pi\Lambda$ or $\pi\Sigma$ pairs is close to the $\Sigma(1385)$ or $\Lambda(1405)$ mass. The only published data of relevance for these processes were obtained at DESY thirty years ago with space-like photons, in electroproduction experiments where the scattered electron and the produced K^+ were detected in coincidence [4]. The differential cross sections for the $e\, p \to e\, K^+\, Y$ reaction in these measurements characterize globally strangeness production processes for hyperon missing masses ranging from 1.35 until 1.45 GeV. The $\Sigma^0(1385)$ and $\Lambda(1405)$ channel cannot be separated, so that the published cross sections are associated with the production of both resonances. An interesting trend of these data is that the t-dependence of the cross section, for given photon energy and virtuality, seems to show a sharp drop as would be expected if the dynamics were dominated by t-channel exchanges. It is best fitted precisely by the double kaon pole $[1/(m_K^2 - t)^2]$ [3]. The Mandelstam variable t is defined as the square of the 4-momentum transfer from the proton target to the $\Sigma^0(1385)$ or $\Lambda(1405)$. We caution that these electroproduction data have very large error bars and should be viewed as an mere indication that our suggestion is not in contradiction with existing experimental information.

There are on the other hand ongoing and future programs pertaining directly to the study of the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions, where the resonances will be separated. The $\Sigma^0(1385)$ decays into neutral ($\pi^0\Lambda$) and charged ($\pi^+\Sigma^-$, $\pi^-\Sigma^+$) channels; its decay into a $\pi^0\Sigma^0$ pair is forbidden. The $\Lambda(1405)$ decays into all $\pi\Sigma$ channels ($\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$). The $\pi^0\, \Sigma^0$ decay is therefore a unique signature of the $\Lambda(1405)$. The measurement of the $\gamma\, p \to K^+\, \pi^0\, \Sigma^0$ reaction is intended at ELSA (Bonn) where the $\pi^0\, \Sigma^0$ pair could be detected through a multi-photon final state ($\pi^0\, \Sigma^0 \to \pi^0\, \Lambda(1116)\, \gamma \to \pi^0\, n\, \pi^0\, \gamma \to n\, 5\gamma$) with the Crystal Barrel [5]. Similarly the $\Sigma^0(1385)$ could be studied by its $\pi^0\, \Lambda$ decay into the $n\, 4\gamma$ channel. The charged channels were also studied at ELSA with the SAPHIR detector. The $\gamma\, p \to K^+\, \pi^+\, \Sigma^- \to K^+\, \pi^+\, \pi^-\, n$ and the $\gamma\, p \to K^+\, \pi^-\, \Sigma^+ \to K^+\, \pi^-\, \pi^+\, n$ reactions (where all charged hadrons are detected) have been investigated in the energy range $1.3 < E_\gamma < 2.6$ GeV [6]. The charged channels are also presently studied at SPring-8/LEPS with incident photon energies in the range $1.5 < E_\gamma^{Lab} < 2.4$ GeV [7]. The analysis of both the SAPHIR and LEPS data is in progress. These data are dominated by effects arising from the presence of the $\Lambda(1405)$ resonance.

We expect these data to be quite accurate and to unravel the dynamics underlying the $\Sigma^0(1385)$ and $\Lambda(1405)$ production for photon laboratory energies ranging from threshold kinematics until the 2 GeV region addressed in this work. Angular or t-distributions in successive energy bins should carry that information.

3 Dynamics of the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions

The dynamics of the $\gamma\, p \to K^+\, \pi^0\, \Lambda(1116)$ and $\gamma\, p \to K^+\, \pi\, \Sigma(1192)$ reactions in the region where the invariant mass of the $\pi\Lambda$ or $\pi\Sigma$ pairs is close to the $\Sigma(1385)$ and $\Lambda(1405)$ masses reflects the nature of these resonances.

The $\Sigma(1385)$ arises as a member of the ground state decuplet of baryons in the large N_c limit of QCD. It is well described by quark models [8, 9] and has a Breit-Wigner shape [10].

The $\Lambda(1405)$ is a complex baryonic state. Its mass, in particular the large splitting between the $\Lambda_{1/2^-}(1405)$ and the $\Lambda_{3/2^-}(1520)$, cannot be understood in the constituent quark model with residual quark-quark interactions fitting the other low-lying baryonic states [8, 9]. Sizeable $q^4\bar{q}$ components seem required [11]. The $\Lambda(1405)$ has been described as a bound kaon-nucleon system [12, 13], in particular as a kaon-soliton bound state [14, 15]. The $\bar{K}N$ nature of the $\Lambda(1405)$ was also inferred from the SU(3) cloudy bag model description [16, 17]. Extensive studies of the $\Lambda(1405)$ based on chiral Lagrangians [2, 18] suggest that this resonance is generated by meson-baryon interactions. The spectral shape of the $\Lambda(1405)$ departs from a Breit-Wigner [19]. It depends strongly on the initial and final states through which it is measured, emphasizing the need for a full understanding of the coupling of the $\Lambda(1405)$ to its different decay channels.

We study the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions with the idea of using future accurate data on these processes (mainly t-distributions) to gain understanding of the $K^-p \to \pi^0\Lambda$ and of the $K^-p \to \pi\Sigma$ amplitudes below the $\bar{K}N$ threshold, where they are dominated by the $\Sigma(1385)$ and $\Lambda(1405)$ resonances.

This procedure requires that these reactions be significantly driven by the process in which the ingoing photon dissociates into a real K^+ and a virtual K^-, the off-shell K^- scattering subsequently off the proton target to produce the $\pi^0\, \Lambda$ or $\pi\, \Sigma$ pair. The corresponding diagrams are displayed in Fig. 1. Such dynamics would show in a sharp drop of the differential cross sections $d\sigma/dt$ with increasing $|t|$ (as suggested by the scarce data available [4]). This drop can have both a double pole component behaving like $1/(m_K^2 - t)^2$ and a single pole dependence going like $1/(m_K^2 - t)$. The new data expected in the near future should make it possible to separate these terms by expressing the differential cross sections $d\sigma/dt$ as a superposition of double and single K^- pole terms and less singular contributions. To support further our t-channel approach, it should be noted that there are no reasons to expect significant s-channel contributions to the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions at $E_\gamma \simeq 2$ GeV. The corresponding total center of mass energy is $\sqrt{s} = 2.15$ GeV. There are no baryon resonances in that mass range known to decay into the $K^+\pi^0\Lambda$ or $K^+\pi\Sigma$ channels. Effects from u-channel contributions are not expected at low t.

We have computed the K^--exchange graphs of Fig. 1 using the chiral coupled-channel approach of kaon-nucleon scattering developed in Ref. [2]. The different nature of the $\Sigma(1385)$ and of the $\Lambda(1405)$ resonances is part of that picture. The baryon resonances belonging to the large N_c ground state baryon mutiplets (hence the $\Sigma(1385)$) are introduced explicitly as fundamental fields of the effective Lagrangian. The other baryon resonances (in particular the $\Lambda(1405)$) are generated dynamically by meson-baryon coupled-channel dynamics. This effective field theory achieves an excellent description of the available data on $K^-\, p$ elastic (direct and charge-exchange) and inelastic ($\pi^0\, \Lambda$, $\pi^+\, \Sigma^-$, $\pi^0\, \Sigma^0$, $\pi^-\, \Sigma^+$) processes up to laboratory K^- momenta of the order of 500 MeV. The interest of the present work is to offer the possibility of testing the amplitudes below the $\bar{K}N$ threshold, in the region where they are dominated by the $\Lambda(1405)$ and the $\Sigma(1385)$. The specific spectral shape of these resonances is a particularly meaningful prediction of the description of Ref. [2]

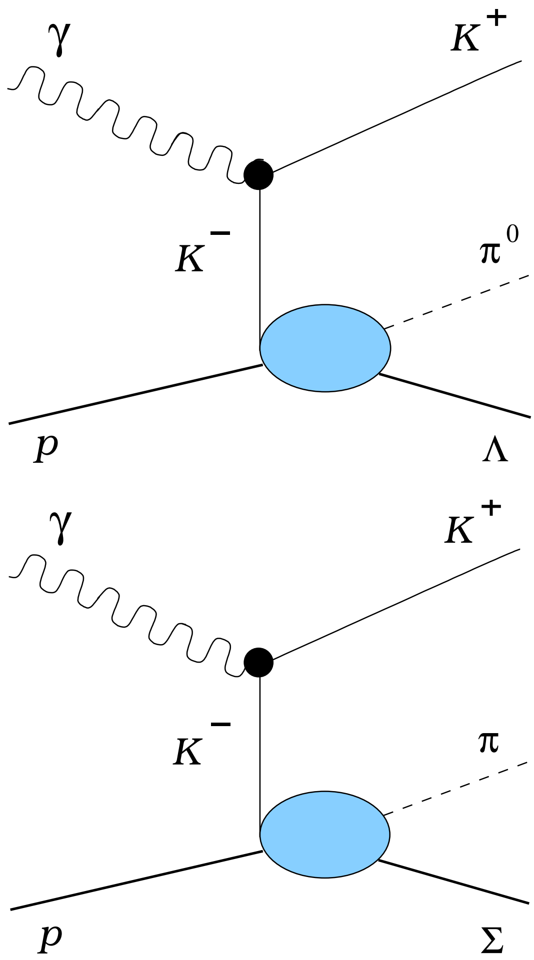

Figure 1: K$^-$-exchange contribution to the $\gamma\, p \to K^+ \pi^0 \Lambda$ amplitude (upper graph) and to the $\gamma\, p \to K^+ \pi \Sigma$ amplitude (lower graph). The $\pi\Sigma$ symbol stands for $\pi^-\Sigma^+$, $\pi^0\Sigma^0$ or $\pi^+\Sigma^-$ in the latter case.

We calculate the cross section for the $\gamma\, p \to K^+\, \pi\, Y$, where Y represents either the $\Lambda(1116)$ or the $\Sigma(1192)$. The 4-momenta of the photon, the proton, the K$^+$, the pion and the hyperon are denoted by q, p, $\bar{q}_K$, $\bar{q}_\pi$ and $\bar{p}_Y$ respectively. The photon, proton and hyperon polarizations are indicated by the symbols λ_γ, λ and $\bar{\lambda}_Y$. The total cross section reads

$$\begin{aligned}\sigma_{\gamma\, p \to K^+\, \pi\, Y} \;\; &= \;\; \frac{1}{|\vec{v}_\gamma - \vec{v}_p|}\, \frac{1}{2\, q^0}\, \frac{m_p}{p^0} \int \frac{d^3\vec{\bar{q}}_K}{(2\pi)^3}\, \frac{1}{2\, \bar{q}^{\,0}_K} \int \frac{d^3\vec{\bar{q}}_\pi}{(2\pi)^3}\, \frac{1}{2\, \bar{q}^{\,0}_\pi} \int \frac{d^3\vec{\bar{p}}_Y}{(2\pi)^3}\, \frac{m_Y}{\bar{p}^{\,0}_Y} \\ &\quad (2\,\pi)^4\, \delta^4(q + p - \bar{q}_K - \bar{q}_\pi - \bar{p}_Y) \sum_{\lambda_\gamma, \lambda, \bar{\lambda}_Y} \frac{1}{4}\, |M_{\gamma\, p \to K^+\, \pi\, Y}|^2. \end{aligned} \tag{1}$$

Factorizing the full amplitude $M_{\gamma\, p \to K^+\, \pi\, Y}$ into the photon-kaon vertex and the $K^-\, p \to \pi\, Y$ amplitude, we can express the $\gamma\, p \to K^+\, \pi\, Y$ cross section in terms of the $K^-\, p \to \pi\, Y$ cross section [3]. The latter is frame-independent and calculated for simplicity in the $K^-\, p$ center of mass. It is useful to define the invariant mass $\sqrt{\bar{w}^2}$ of the final $\pi\, Y$ pair by

$$\bar{w}^2 = (p + q - \bar{q}_K)^2 = s + m_K^2 - 2\, \sqrt{s}\, \sqrt{m_K^2 + \vec{\bar{q}}_K^{\,2}}. \tag{2}$$

The expression for the total $K^- p \to \pi Y$ cross section is given by

$$\sigma_{K^-p\to\pi Y} = \frac{1}{\sqrt{\bar{w}^2}\,|\vec{q}_{K^-p}|}\frac{m_p}{2}\int\frac{d^3\vec{\bar{q}}_\pi}{(2\pi)^3}\frac{1}{2\,\bar{q}^{\,0}_{\pi}}\int\frac{d^3\vec{\bar{p}}_Y}{(2\pi)^3}\frac{m_Y}{\bar{p}^{\,0}_Y}$$
$$(2\,\pi)^4\,\delta^4(\bar{w}-\bar{q}_\pi-\bar{p}_Y)\,\frac{1}{2}\sum_{\lambda,\bar{\lambda}_Y}|M_{K^-p\to\pi Y}|^2, \qquad (3)$$

in which q_{K^-p} is the K^- momentum in the K^-p center of mass,

$$|\vec{q}_{K^-p}|^2 = \frac{1}{4\,\bar{w}^2}\,\{\bar{w}^4 - 2\,\bar{w}^2\,(m_p^2+m_K^2)+(m_p^2-m_K^2)^2\}, \qquad (4)$$

and the amplitudes $M_{K^-p\to\pi Y}$ are taken from Ref. [2].

In the energy range under consideration ($E_\gamma \simeq 2$ GeV), there are many possible diagrams contributing to the $\gamma\, p \to K^+\,\pi\, Y$ amplitudes and involving poorly known couplings and hence large uncertainties. The amplitudes $M_{\gamma p\to K^+\pi Y}$ obtained by calculating the graphs of Fig. 1 are not gauge-invariant. To obtain the full gauge-invariant amplitudes, a large class of diagrams of order α leading to the same final state should be added. We do not attempt to calculate these graphs and resort instead to the pole scheme method [20]. The idea of the method is to decompose the amplitude according to its pole structure and to expand it around the pole. To any order in perturbation theory, the residues of the poles are gauge-invariant. We apply this method to derive the gauge-invariant cross section corresponding to the double K$^-$-pole term. The key point is that the graphs of Fig. 1 are the only process which can contribute to the double K$^-$-pole term. We will therefore decompose the corresponding cross section according to its pole structure, keep only the double K$^-$-pole term and extract the gauge-invariant cross section associated with that pole structure by calculating the residue at the pole.

According to this procedure, the gauge-invariant cross section corresponding to the double K$^-$-pole term reads

$$\frac{d\sigma_{\gamma\,p\to K^+\,\pi\,Y}}{dt\,d\bar{w}^2} = \frac{\alpha}{2\,\pi}\,\frac{(\bar{w}^4-2\,\bar{w}^2\,(m_p^2+m_K^2)+(m_p^2-m_K^2)^2)^{1/2}}{(s-m_p^2)^2}$$
$$\frac{m_K^2}{(t-m_K^2)^2}\,\sigma_{K^-\,p\to\pi\,Y}(\bar{w}^2). \qquad (5)$$

We stress that the double pole term is the only one which can be determined this way, because it does not get contributions from any other graph but the t-channel kaon-exchange diagram.

In order to be able to extract the double pole term from accurate t-distributions, it has to be reasonably large. We speculate so in view of the numerical results displayed in the next section. As mentioned earlier and discussed more thoroughly in Ref. [3], the double pole behaviour is also compatible with the few data points available.

4 Numerical results

We show first the quantity $4\,|\vec{q}_{K^-p}|\sqrt{\bar{w}^2}\;\sigma_{K^-\,p\to\pi\,Y}(\bar{w}^2)$ as function of the total center of mass energy in the K^-p system, renamed for clarity $\sqrt{s_{K^-p}}$ ($\equiv \sqrt{\bar{w}^2}$). The interest of displaying our results this way is to exhibit the behaviour of the $K^-\,p \to \pi\,Y$ cross section across threshold. We recall that the $\bar{K}N$ threshold is at $\sqrt{s_{K^-p}}\approx 1.435$ GeV. We present for example in Fig. 2 our predicted cross sections for the $K^-\,p\to\pi^0\,\Sigma^0$ and $K^-\,p\to\pi^0\,\Lambda$ reactions. They are compared to the data available on these processes above threshold [21, 22, 23, 24].

We recall that the $\pi^0\,\Sigma^0$ channel reflects the $\Lambda(1405)$ and the $\pi^0\,\Lambda$ channel the $\Sigma(1385)$. The properties of the spectral functions of the $\Sigma(1385)$ and $\Lambda(1405)$ resonances are very apparent in Fig. 2.

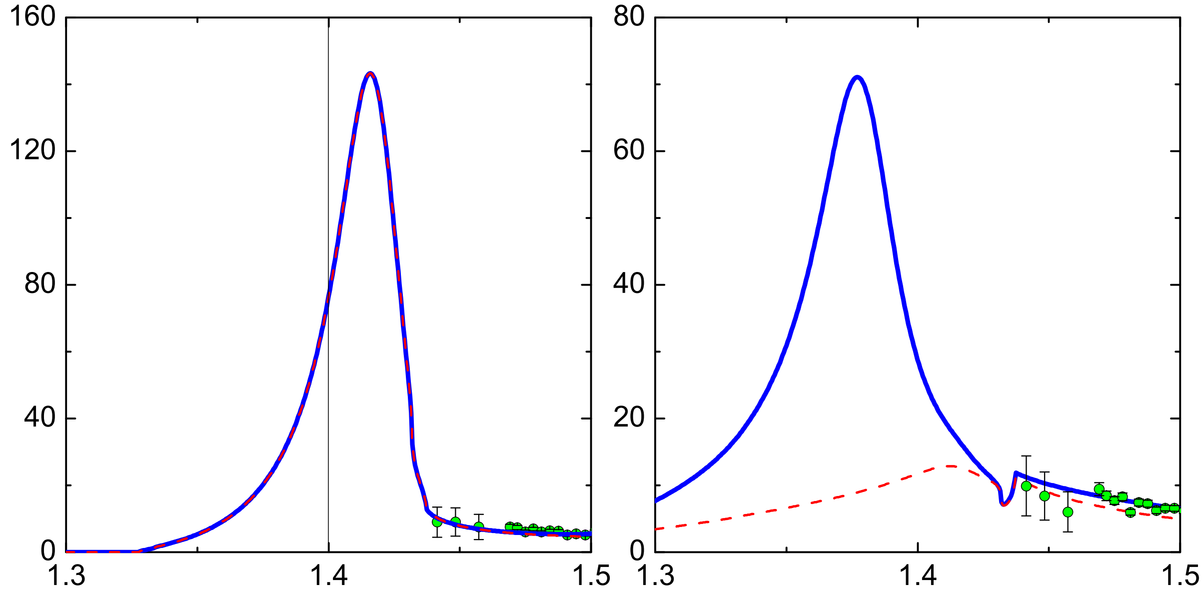

Figure 2: $K^- p \to \pi^0 \Sigma^0$ and $K^- p \to \pi^0 \Lambda$ cross sections below and above threshold. The length of the K^- 3-momentum is defined by Eq. (4) and $\sqrt{s_{K^-p}}$ ($\equiv \sqrt{\bar{w}^2}$) is the total center of mass energy of the $K^- p$ system. The dashed line represents the contribution from $K^- p$ relative s-wave only. The data above threshold are from Refs. [21, 22, 23, 24].

The shape of the resonant behaviour of the $K^- p \to \pi^0 \Lambda$ cross section below threshold is quite symmetric and close to a Breit-Wigner form. The s-wave contribution is small as expected for a process dominated by a p-wave resonance. In contrast, the spectral form of the $K^- p \to \pi^0 \Sigma^0$ cross section is asymmetric and largely given by s-wave dynamics, reflecting the $\Lambda(1405)$ dominance.

We display in Fig. 3 the double kaon pole term contributions to the differential cross sections for the $\gamma p \to K^+ \pi^0 \Lambda$ and $\gamma p \to K^+ \pi \Sigma$ reactions as functions of the πY total center of mass energy $\sqrt{s_{K^-p}}$ at $E_\gamma = 2.1$ GeV.

We see clearly the dynamical features discussed in commenting on Fig. 3. It is also interesting to note the absolute values of the double kaon pole cross sections. They are large on the scale of what is expected from other theoretical approaches. If we compare our results to the predictions of the model of Ref. [25] at $E_\gamma = 1.7$ GeV, we notice that our calculated cross sections at that energy are roughly twice larger for the $\pi \Sigma$ channels [3]. It is not easy to trace the origin of this effect. Our gauge-invariant double kaon pole term contains contributions which cannot be mapped easily onto the Feynman diagrams computed in Ref. [25]. The cross section we obtain for the $\pi^0 \Lambda$ channel is about an order of magnitude larger than the result displayed in Ref. [25]. A substantial part of this effect should be ascribed to the neglect of the $\Sigma(1385)$ resonance in that work.

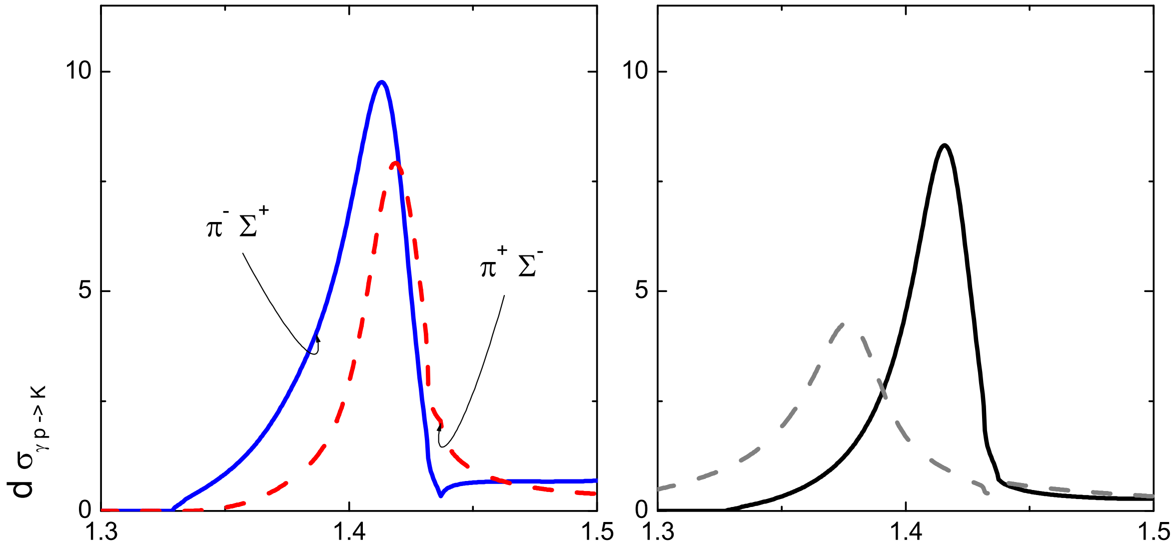

Figure 3: Double kaon pole term contribution to the differential cross sections for the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions as function of the πY total center of mass energy at $E_\gamma = 2.1$ GeV

5 Conclusion

We have studied the $\gamma p \to K^+\pi^0\Lambda$ and $\gamma p \to K^+\pi\Sigma$ reactions in the kinematic region where the $\pi^0\Lambda(1116)$ and $\pi\Sigma(1192)$ pairs originate dominantly from the decay of the $\Sigma(1385)$ and $\Lambda(1405)$ resonances. We focus on laboratory photon energies around 2 GeV, significantly above the threshold for producing the $K^+\,\Sigma(1385)$ ($\mathrm{E}_\gamma^{thresh}$=1.41 GeV) and the $K^+\,\Lambda(1405)$ ($\mathrm{E}_\gamma^{thresh}$=1.45 GeV) final states. We have calculated the t-channel K^--exchange contribution to these reactions using the $K^-\,p \to \pi\,Y$ amplitudes of Ref. [2], which have been shown to describe the data available at low kaon momentum. Based on the pole structure of this contribution, we determined the gauge-invariant double kaon pole contribution to the $\gamma p \to K^+\pi Y$ cross sections by calculating the residue at the pole. The relevance of our work stems from the advent of detector systems able to measure exclusively multiparticle final states with great accuracy. Three complementary experiments in the photon energy range considered in this paper are planned with LEPS at SPring-8 [7], SAPHIR at ELSA [6] and the Crystal Barrel at ELSA [5], dealing for the first two with the charged [$\pi^-\Sigma^+$ and $\pi^+\Sigma^-$] channels and for the latter with the neutral [$\pi^0\Sigma^0$ and $\pi^0\Lambda$] final states. These accurate measurements should make it possible to extract the contribution of the double kaon pole and hence to study kaon-nucleon dynamics below threshold.

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