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# Regge-plus-resonance predictions for kaon photoproduction from the neutron

P. Vancraeyveld *, L. De Cruz, J. Ryckebusch, T. Van Cauteren

*Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium*

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ABSTRACT

We present predictions for $n(\gamma, K^+)\Sigma^-$ differential cross sections and photon-beam asymmetries and compare them to recent LEPS data. We adapt a Regge-plus-resonance (RPR) model developed to describe photoinduced and electroinduced kaon production off protons. The non-resonant contributions to the amplitude are modelled in terms of $K^+(494)$ and $K^{*+}(892)$ Regge-trajectory exchange. This amplitude is supplemented with a selection of $s$-channel resonance diagrams. The three Regge-model parameters of the $n(\gamma, K^+)\Sigma^-$ amplitude are derived from the ones fitted to proton data through $SU(2)$ isospin considerations. A fair description of the $n(\gamma, K^+)\Sigma^-$ data is realised, which demonstrates the Regge model's robustness and predictive power. Conversion of the resonances' couplings from the proton to the neutron is more challenging, as it requires knowledge of the photocoupling helicity amplitudes. We illustrate how the uncertainties of the helicity amplitudes propagate and heavily restrain the predictive power of the RPR and isobar models for kaon production off neutron targets.


Mapping out the baryonic spectrum remains a paramount issue in hadron physics. The masses, widths and transition form factors of the nucleon's excited states are invaluable input to models aimed at understanding the internal structure of baryons. In this regard, electromagnetic (EM) kaon production plays a key role in the ongoing theoretical and experimental efforts to explore the dynamics of QCD in the confinement regime.

Electron accelerator facilities, such as ELSA, Jefferson Lab, MAMI and SPring-8, are making contributions to a "complete" kaon production experiment. Along with the unpolarised differential cross section, this requires the measurement of seven carefully chosen single and double polarisation observables [1,2]. Ideally, this leads to an unambiguous determination of the reaction amplitude and, as such, stringent constraints on dynamical models. Thus far, the lion's share of research efforts has been directed towards reactions off proton targets. The complementary reaction on neutrons yields additional constraints that help to further pin down the underlying reaction dynamics. Moreover, the neutron channels are a crucial ingredient in the description of hypernuclear spectroscopy and quasi-free kaon production on nuclei. These reactions provide, amongst other things, access to the hyperon–nucleon interaction [3].

The presence of open strangeness in the final state of electromagnetic kaon production holds out the prospect of finding some elusive resonant states. Despite the publication of a large body of high-quality $p(\gamma^{(*)}, K)Y$ data in recent years, phenomenological analyses have not led to an unequivocal outcome. Disentangling the relevant resonant contributions is challenging, because of the large number of competing resonances above the kaon production threshold. Moreover, the smooth energy dependence of the measured observables hints at a dominant role for the background, i.e. non-resonant, processes. Hence, the treatment of the background is pivotal for any model. In traditional isobar approaches, these non-resonant terms diverge as energy increases [4]. Over the years, several mechanisms to remedy this unrealistic behaviour have been proposed. The extracted resonance couplings, however, heavily depend on the background model [5,6].

At sufficiently high energies, the isobar description is no longer optimal. In this energy region, the kaon production amplitude can be elegantly described within the Regge framework, characterised by the exchange of whole families of particles, instead of individual hadrons [7]. Interestingly, the Regge model, a high-energy theory by construction, allows to describe the gross features of the data in the resonance region [8–10]. Extrapolating the Regge model to intermediate energies results in a reliable account of the kaon-production background within the resonance region and imposes a proper high-energy behaviour.

Building upon the work of Guidal et al. [7,11], we model the $p(\gamma, K^+)\Sigma^0$ background amplitude by means of $K^+(494)$ and

* Corresponding author.
*E-mail address:* Pieter.Vancraeyveld@UGent.be (P. Vancraeyveld).

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$K^{*+}(892)$ Regge-trajectory exchange in the $t$-channel [10]. A gauge invariant amplitude is obtained by adding the electric part of the nucleon $s$-channel Born diagram. The strong forward-peaked character of the differential cross section provides powerful support for this approach. The exchange of a linear kaon Regge-trajectory

$$\alpha_{K^{(*)+}}(t) = \alpha_{K^{(*)+},0} + \alpha'_{K^{(*)+}}\left(t - m^2_{K^{(*)+}}\right), \quad (1)$$

with $m_{K^{(*)+}}$ and $\alpha_{K^{(*)+},0}$ the kaon's mass and spin, is realised through a Reggeized amplitude that combines elements of the Regge formalism and a tree-level effective-Lagrangian model. Reggeization amounts to replacing the standard Feynman $(t - m^2_{K^{(*)+}})^{-1}$ propagator by the corresponding Regge propagator

$$\mathcal{P}^{K^+(494)}_{\text{Regge}}(s,t) = \left(\frac{s}{s_0}\right)^{\alpha_{K^+}(t)} \frac{e^{-i\pi\alpha_{K^+}(t)}}{\sin(\pi\alpha_{K^+}(t))} \frac{\pi\alpha'_{K^+}}{\Gamma(1+\alpha_{K^+}(t))},$$
$$\mathcal{P}^{K^{*+}(892)}_{\text{Regge}}(s,t) = \left(\frac{s}{s_0}\right)^{\alpha_{K^{*+}}(t)-1} \frac{1}{\sin(\pi\alpha_{K^{*+}}(t))} \frac{\pi\alpha'_{K^{*+}}}{\Gamma(\alpha_{K^{*+}}(t))}, \quad (2)$$

with $s_0 = 1\ \text{GeV}^2$, $\alpha_{K^+}(t) = 0.70\ (t - m^2_{K^+})$ and $\alpha_{K^{*+}}(t) = 1 + 0.85\ (t - m^2_{K^{*+}})$, when $t$ and $m^2_{K^{(*)+}}$ are expressed in units of $\text{GeV}^2$. The data [12,13] indicate that the trajectories are strongly degenerate. Consequently, the Regge propagators have either a constant or rotating phase. These phases cannot be deduced from first principles. In Ref. [10], we found the $p(\gamma, K^+)\Sigma^0$ data to be compatible with a rotating and a constant phase for the $K^+(494)$ and $K^{*+}(892)$ trajectories respectively. In our implementation of the Regge model, the operatorial structure of the amplitudes is dictated by an effective Lagrangian approach,[1] in which the $t$-channel propagators are replaced by the corresponding Regge ones. As a consequence, the amplitude corresponding to $K^{(*)+}$ exchange in the $t$-channel effectively incorporates the transfer of an entire trajectory. When considering the exchange of $K^+(494)$ and $K^{*+}(892)$ trajectories, the Regge model for $p(\gamma, K^+)\Sigma^0$ has a mere three parameters

$$g_{K^+\Sigma^0 p}, \quad G^{v,t}_{K^{*+}\Sigma^0 p} = \kappa_{K^{*+}K^+} \frac{e g^{v,t}_{K^{*+}\Sigma^0 p}}{4\pi}, \quad (3)$$

with $g_{K^+\Sigma^0 p}$, $g^v_{K^{*+}\Sigma^0 p}$ and $g^t_{K^{*+}\Sigma^0 p}$ the coupling constants at the strong interaction vertex and $\kappa_{K^{*+}K^+}$ the $K^{*+}(892)$'s transition magnetic moment.

The Regge model's amplitude can be interpreted as the asymptotic form of the full amplitude for large $s$ and small $|t|$. Owing to the $t$-channel dominance and the absence of a prevailing resonance, the Reggeized background can account for the gross features of the kaon production data within the resonance region [8,10]. Near threshold, the energy dependence of the measured differential cross sections exhibits structure which hints at the presence of resonances. These are incorporated by supplementing the background with a number of resonant $s$-channel diagrams. This approach was coined Regge-plus-resonance (RPR) and has previously been applied to double-pion production [14], as well as the production of $\eta$ and $\eta'$ mesons [15]. We describe the resonant contributions using standard tree-level Feynman diagrams. By substituting $s - m_R^2 \to s - m_R^2 + i m_R \Gamma_R$ in the propagator's denominator, we take into account the finite lifetime of resonances with mass $m_R$ and width $\Gamma_R$. To limit the number of fit parameters, we keep the resonances' mass and width fixed at the values given in the Particle Data Group's Review of Particle Physics (RPP) [16]. Each spin-1/2 resonance introduces one free parameter

$$G_{N^*} = \kappa_{N^* p} \times g_{K^+\Sigma^0 N^*}, \quad (4)$$

the product of the coupling constants at the electromagnetic and the strong interaction vertex. Spin-3/2 resonances have an additional degree of freedom at the photon vertex and give rise to two free parameters

$$G^{(1)}_{N^*} = \kappa^{(1)}_{N^* p} \times g_{K^+\Sigma^0 N^*},$$
$$G^{(2)}_{N^*} = \kappa^{(2)}_{N^* p} \times g_{K^+\Sigma^0 N^*}. \quad (5)$$

The most general interaction Lagrangian for spin-3/2 fields allows for an additional three degrees-of-freedom, often called *off-shell* parameters, in the strong and EM vertices [17]. To ensure that the effects of the resonant diagrams fade at higher energies, we introduce a Gaussian form factor with a cutoff $\Lambda_{\text{strong}} \approx 1.6$ GeV at the strong interaction vertices [10].

The dynamics of electromagnetic kaon production can be fairly involved, with several contributing nucleon and delta resonances that interfere with an eminent background. Disentangling these contributions is challenging. In the RPR approach, we seek to determine the resonant and non-resonant terms separately [9,10]. At sufficiently high energies ($\omega_{\text{lab}} \gtrsim 4$ GeV), a limited amount of 57 $p(\gamma, K^+)\Sigma^0$ data points are available, consisting of differential cross sections [12] and photon-beam asymmetries [13]. These data show no resonant features and are used to constrain the three parameters of the Regge model in Eq. (3). In the resonance region, a large body of data is available [18–21], against which we fit the resonance parameters, while keeping the background unaltered. In Ref. [10], we established the phases of the leading kaon trajectories. With the available 57 data points, it turned out impossible to single out a unique parametrisation of the Regge model, as the sign of $G^t_{K^{*+}\Sigma^0 p}$ remained undetermined. The two model variants, that yield an equally good description of the high-energy data, were labelled Regge-3 and Regge-4. Subsequently, we added resonances to the Reggeized background amplitude, identifying the $S_{11}(1650)$, $D_{33}(1700)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$, $S_{31}(1900)$, $P_{31}(1910)$ and $P_{33}(1920)$ as essential contributions. These are established resonances with a 3- or 4-star status in the RPP [16], except for the $P_{13}(1900)$ and $S_{31}(1900)$, which are 2-star resonances. Both the RPR-3 and RPR-4 models reach a goodness-of-fit of $\chi^2/\text{d.o.f.} = 2.0$. We found no direct need to include "missing" resonances in the $K\Sigma$ channel.

In order to assess the predictive power of the RPR model, we extended our formalism to kaon electroproduction in Ref. [22]. The $Q^2$-dependence of the EM coupling constants was incorporated using transition form factors as computed in the Bonn constituent-quark model [23]. Without refitting any parameters, we found that the RPR model gives a decent account of the available kaon electroproduction data. Kaon production off neutrons offers another opportunity to test the robustness of the RPR approach. In what follows, we will point out how the fitted RPR amplitude for the $p(\gamma, K^+)\Sigma^0$ channel can be transformed with an eye to predicting the $n(\gamma, K^+)\Sigma^-$ reaction.

In order to relate $n(\gamma, K^+)\Sigma^-$ to $p(\gamma, K^+)\Sigma^0$, it suffices to convert the coupling constants which feature in the interaction Lagrangians. In the strong interaction vertex, we assume isospin symmetry to be exact. The hadronic couplings are proportional to the Clebsch–Gordan coefficients:

$$g_{K\Sigma N^{(*)}} \sim \left\langle I_K = \frac{1}{2}, M^I_K; I_\Sigma = 1, M^I_\Sigma \,\middle|\, I_{N^{(*)}} = \frac{1}{2}, M^I_{N^{(*)}} \right\rangle,$$
$$g_{K\Sigma\Delta^*} \sim \left\langle I_K = \frac{1}{2}, M^I_K; I_\Sigma = 1, M^I_\Sigma \,\middle|\, I_\Delta = \frac{3}{2}, M^I_\Delta \right\rangle. \quad (6)$$

We adopt the following conventions for the isospin states of the $N^{(*)}$, $\Delta^*$, $K^{(*)}$ and $\Sigma$ particles,

[1] Our choice of strong and electromagnetic interaction Lagrangians can be found in Ref. [9].