Photoproduction of Strangeness

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PHOTOPRODUCTION OF STRANGENESS

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1 Strangeness

"Strange" particles have been observed for the first time in 1947 by Rochester and Butler at the University of Manchester. These new particles at this time had the “strange” and unexpected characteristic to be produced via strong interactions and to decay by weak interactions with relatively long lifetimes of the order of $10^{-10}$ s.

To explain this “anomaly”, Gell-Mann and independently, Nishijima, proposed in 1954 to associate a new quatum number (strangeness) with these particles which would be conserved in strong interactions and not conserved in weak interactions.

It becomes then natural to extend the symmetry group SU(2) of the strong interactions relating proton and neutron, to SU(3) and therefore investigate hyperon-nucleon interactions on the same foot as nucleon-nucleon interactions. Taking full advantage of the additional degree of freedom introduced by strangeness permits to diversify and broaden our ways to understand the structure and dynamics of hadronic matter.

Strangeness also provides a link between the light and heavy quarks sectors. Whereas chiral symmetry and low-energy theorems allow to strongly constrain the light quark sector, the heavy quark sector is governed by different symmetries.
One can gain understanding of the interactions between nucleons and strange particles by different means: study of hypernuclei (a nuclei where a nucleon is replaced by a hyperon; investigated up to now only via hadronic probes), direct scattering reactions \((K-N, Y-N,\ldots)\), electro- and photo-production of strangeness, \ldots

The particular advantage of the latter reactions is that the electromagnetic interaction is well known. It is easier to disentangle the different mechanisms at stake and to extract the coupling constants involved. Numerous experiments planned at CEBAF (USA), ELSA (Germany) and ESRF (France) will soon provide very precise cross-section and polarization asymmetries data thus motivating development and improvement of theoretical models.

In the following, we will summarize the model developed by Williams-Ji-Cotanch [1] presented in the 1994 HUGS lectures, describing the most fundamental and elementary strangeness electro- and photo-production reactions in the intermediate energy region \((\sqrt{s} < 2.5 \text{ GeV})\):

\[
\begin{align*}
\gamma^{(*)} + p &\rightarrow K^+ + \Lambda \\
\gamma^{(*)} + p &\rightarrow K^+ + \Sigma^0
\end{align*}
\]

where \(\gamma^*\) stands for a virtual photon. We will focus here on the photoproduction reactions, the model being readily extensible to electro-production. This paper is extensively inspired from R. Williams thesis [2] where all the figures and more detailed discussion can be found.

## 2 Model Description

The model is based on an effective Lagrangian formalism with hadronic degrees of freedom, which is certainly the most natural description in the energy domain we consider. This Lagrangian can be decomposed in terms of free \((\mathcal{L}_0)\) and interacting \((\mathcal{L}_I)\) parts:

\[
\mathcal{L} = \sum_f \mathcal{L}^f_0 + \mathcal{L}_I
\]

where the index \(f\) stands for the following hadronic fields:

\[
\{f\} \equiv \{\Lambda, \Sigma^0, \Lambda^*(1405), \Lambda^*(1670), \Lambda^*(1800), K, K^*(890), K1(1290), p, N^*(1470), \}
\]
\[ N^*(1550), N^*(1710), \Delta(1620), \Delta(1900), \Delta(1910) \}

leading to the following \textit{free} Lagrangians:

\[
\mathcal{L}_0^{\text{fermions}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi
\]

\[
\mathcal{L}_0^{\text{scalar}} = \partial_\mu \phi^i \partial^\mu \phi - m^2 \phi^i \phi^i
\]

\[
\mathcal{L}_0^{\text{vector}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - M_V^2 |V|^2
\]

The interaction Lagrangian involves both electromagnetic and hadronic terms:

\[
\mathcal{L}_I^{EM} = -e (J_\mu^1 + J_\mu^2) A_\mu - i\mu_{\bar{\nu}} \bar{p} \sigma^{\mu \nu} p + \mu_\Lambda \bar{\Lambda} \sigma^{\mu \nu} \Lambda + \mu_\Lambda \bar{\Lambda} \sigma^{\mu \nu} \Lambda^* F^{(A)}_{\mu \nu}
\]

\[
- \frac{i}{2} \mu_\Lambda^{(N^+)p} \bar{p} \sigma_{\mu \nu} \Gamma_\Lambda(\pm) N^* + \mu_\Lambda^{(\Delta^+)p} \bar{p} \sigma_{\mu \nu} \Gamma_\Lambda(\pm) \Delta^* F^{(A)}_{\mu \nu}
\]

\[
-i \frac{g_k^* K^*}{m} \varepsilon^{\mu \nu \rho \sigma} K \partial_\mu K^* \partial_\nu A_\rho - \frac{g_k^* K^*}{m} (K \partial^\mu K^* - \Lambda \partial^\mu K^* \partial_\mu A_\rho
\]

and

\[
\mathcal{L}_I^{\text{hadronic}} = g_{KN \Lambda}[\bar{N} \gamma_\mu \Lambda K + \bar{K} \Lambda \gamma_\mu N] + g_{KN \Lambda^*}[\bar{N} \Lambda^* K + \bar{K} \Lambda^* N]
\]

\[
+ g_{K \Sigma}[\bar{N} \gamma_\mu \Sigma K + \bar{K} \Sigma \gamma_\mu N] + g_{K \Sigma \Delta}[\bar{N} \gamma_\mu \Sigma K + \bar{K} \Sigma \gamma_\mu N] + g_{K \Sigma \Delta}[\bar{N} \gamma_\mu \Sigma K + \bar{K} \Sigma \gamma_\mu N]
\]

\[
- i g_{K_\mu}(\pm) N [\bar{N} \gamma_\mu \gamma_\rho \Lambda K^* - \bar{K} \Lambda^* \gamma_\rho \Lambda N]
\]

\[
- i g_{K_\mu}(\pm) N [\bar{N} \gamma_\mu \gamma_\rho \Lambda K^* - \bar{K} \Lambda^* \gamma_\rho \Lambda N]
\]

\[
- i g_{K_\mu}(\pm) N [\bar{N} \gamma_\mu \gamma_\rho \Lambda K^* - \bar{K} \Lambda^* \gamma_\rho \Lambda N]
\]

\[
- i g_{K_\mu}(\pm) N [\bar{N} \gamma_\mu \gamma_\rho \Lambda K^* - \bar{K} \Lambda^* \gamma_\rho \Lambda N]
\]

\[
- i g_{K_\mu}(\pm) N [\bar{N} \gamma_\mu \gamma_\rho \Lambda K^* - \bar{K} \Lambda^* \gamma_\rho \Lambda N]
\]
The model is completely defined by this Lagrangian. To calculate matrix elements, the Feynman diagrams of fig. 1 have been considered.

Underlying to this model is the fundamental concept of *duality*. Duality states that including all the resonances in both *s-* (u-) and *t-* channels simultaneously leads to double-counting. For instance, Schmid [3] was able to explain *s-*channel resonances in terms of simple *t-*channel Regge-pole exchanges. Conversely, including $K^*$, $K1$, *t-*channel resonances in the present model should account for the high-spin *s-*channel resonances, not considered here.

### 3 Numerical Results

The idea is now to calculate observables (total, differential cross-sections, polarization observables,...) and fit the unknowns of the model (the coupling constants, $g_{K\Lambda N}$, $g_{K\Lambda N}$,...) so as to reproduce the experimental data. For example, in the case of *photo-*production, given the expression of the matrix element $\mathcal{M}_{f_i}$ (calculated from the Feynman diagrams), one can derive the differential cross-section and the single polarization asymmetries of the $\Lambda$ ($P$), of the photon ($\Sigma$) and of the proton ($T$):

\[
d\sigma = (2\pi)^4 \frac{M_P M_\Lambda | \mathcal{M}_{f_i} |^2 \delta^{(4)}(p_p + p_\gamma - p_K - p_\Lambda) \, d^3p_K \, d^3p_\Lambda}{4E_\Lambda E_\gamma [(p_p-p_\gamma)^2 - p_p^2 p_\gamma^2]^{1/2}} (2\pi)^3 (2\pi)^3
\]

\[
  P = \frac{d\sigma^+}{dn} - \frac{d\sigma^-}{dn}
  \quad P = \frac{d\sigma^+}{dn} + \frac{d\sigma^-}{dn}
\]

\[
  \Sigma = \frac{d\sigma^\perp}{dn} - \frac{d\sigma^\parallel}{dn}
  \quad \Sigma = \frac{d\sigma^\perp}{dn} + \frac{d\sigma^\parallel}{dn}
\]

\[
  T = \frac{d\sigma^\perp}{dn} - \frac{d\sigma^-}{dn}
  \quad T = \frac{d\sigma^\perp}{dn} + \frac{d\sigma^-}{dn}
\]

where $\perp$ (\parallel) refers to a parallel (antiparallel) polarization of the proton or the $\Lambda$ respective to the *y-*axis, and $\perp$ (\parallel) refers to the photon polarization perpendicular (parallel) to the reaction plane.
The choice of the resonances involved is not unique and different configurations have to be tested. However, a strong constraint is imposed to the fits by requiring the model to account for the data of the crossing related reactions.

Crossing symmetry stems from the Lorentz invariance of the operators and states that the same amplitude should describe reactions involving particles in the initial/final state and reactions with the corresponding antiparticles in the final/initial state. For instance, the amplitude for the photoproduction process $\gamma p \rightarrow K^+ Y$ should readily yield the amplitude for the radiative capture process $K^- p \rightarrow \gamma Y$, with $Y \equiv \Lambda, \Sigma^0$.

The only experimental data available for kaon capture processes are the electromagnetic branching ratios [5]:

$$B_{\Lambda}^{exp} \equiv \frac{\Gamma_{K^- p \rightarrow \gamma \Lambda}}{\Gamma_{K^- p \rightarrow all}} = (0.86 \pm 0.07 \pm 0.09) \times 10^{-3}$$

$$B_{\Sigma^0}^{exp} \equiv \frac{\Gamma_{K^- p \rightarrow \gamma \Sigma^0}}{\Gamma_{K^- p \rightarrow all}} = (1.44 \pm 0.12 \pm 0.11) \times 10^{-3}$$

One could also further constrain the model by retaining only the configurations yielding values of the coupling constants in agreement with predictions arising from SU(3) symmetry considerations, as done by Adelseck-Saghai [4]. This is not the case here however.

The following set of figures show a selection of numerical results produced by the model and compared with experimental data.

Fig. 2 displays the $K$-$\Lambda$ photoproduction cross section angular distribution at $E_{lab}=1.2$ GeV, for 2 sets of parameters (whose numerical values can be found in [2] p.44). The figure also shows the model of Adelseck, Wright and Bennhold [6] (dotted curve) which match correctly the data points but does not yield the $B_\Lambda$ branching ratio.

Fig. 3 displays the $\Lambda$ polarization at $\theta_{c.m.}=90^\circ$ versus the lab photon energy. While all four curves reproduce correctly the data points, the poor experimental accuracy does not allow to favor any particular one. More generally, one should notice that polarization observables are very sensitive to the different reaction mechanisms and more precise data should allow to distinguish them. One should stress here that $\Lambda$ and $\Sigma$ production experiments...
are self-analyzing, i.e., that the angular distribution of their decay products readily yields their polarization. In the same order of idea, fig. 4 shows the kaon capture cross section predictions which exhibits a strong sensitivity to the various models.

At higher lab photon energy, fig. 5 shows the influence of the \( t \)-channel resonances: the dash-dotted curve represents the model without the \( K^*(892) \) and \( K_1(1270) \) graphs, while they are incorporated in the solid curve. This goes in the direction mentioned earlier: the higher the lab photon energy, the more high spin \( s \)-channel resonances contribute which, by virtue of the duality principle, are accounted for by exchange of \( t \)-channel resonances.

4 Conclusion

This paper intended to give an outline of the phenomenological model developed by Williams-Ji-Cotanch to describe electromagnetic production processes. The model is very successful in reproducing the existing experimental data for both hyperon photoproduction and crossed symmetry radiative \( K \) capture.

However, one should stress that the approach adopted here is not unique. David et al. [8], for instance, explicitly introduced spin \( \frac{3}{2} \) and \( \frac{5}{2} \) nucleonic resonances (while the model presented here supposes that the \( K^* \) and \( K' \) resonances are sufficient to "simulate" them) and are able to derive coupling constants values in agreement with SU(3) predictions, with the same constraints imposed to the model (fit to the data, crossing requirement,...). Also, this is done at the price of introducing a larger set of parameters.

There are no doubts that, after the lack of new data for almost 20 years now, the next generation of experiments will provide high precision reliable data and allow to distinguish between the various approaches.

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References


$s$-channel graphs:

$t$-channel graphs:

$u$-channel graphs:

Figure 1: Diagrams used in the model for $p(\gamma, K^+)Y$ and $p(K^-, \gamma)Y$ for $Y = \Lambda, \Sigma^0, \Lambda(1405)$. \{N$^*$\} $\equiv$ \{N(1470), N(1580), N(1710)\}, \{\Lambda$^*$\} $\equiv$ \{\Lambda(1405), \Lambda(1670), \Lambda(1800)\}, \{\Delta$^*$\} $\equiv$ \{\Delta(1620), \Delta(1900), \Delta(1910)\}, \{K$^*$\} $\equiv$ \{K$^*$(892), K$^*$1(1270)\}. 
Figure 2: Kaon $\Lambda$ photoproduction cross section angular distribution for models C1 (solid line), C2 (dashed), model of ref.[6] (dotted).

Figure 3: Energy dependence of the $\Lambda$ polarization predicted by three models with the same labeling as fig. 2. The dashed dotted curve is a crossed kaon capture model prediction [7].
Figure 4: Kaon capture cross section predictions with the same labeling as fig. 3.

Figure 5: \( p(\gamma, K^+)\Lambda \) photoproduction cross section at \( \theta_{\text{c.m.}} \sim 27^\circ \). The solid curve represents the model including the \( K^+(892) \) and \( K_1(1270) \) graphs while the dash-dotted curve reproduces the model excluding these graphs.