

THE STUDY OF THE ELEMENTARY PHOTO- AND ELECTRO-PRODUCTION OF KAONS AT JEFFERSON LAB

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The subject of electromagnetic production of strangeness, covers an important part of the planned CEBAF experimental program at Jefferson Lab. In this review we will mainly focus on those experiments aiming to investigate the elementary mechanism of the associated production of kaon-hyperon pairs, on hydrogen target, induced by electron and by real photon beams. Complementary experiments, proposed for all the three experimental halls, allow to access a wide kinematical region where different theoretical approaches can be used for the interpretation of the (upcoming) data.

1 Introduction

The construction of the Continuous Electron Beam Accelerator Facility is now completed at Jefferson Lab (JLab in Virginia, USA). The accelerator delivers three simultaneous electron beams into three experimental halls with independent energy and intensity. The maximum energy now available is 4 GeV, but, due to the very good performances of the superconducting cavities, it is supposed that, with only minor changes to the accelerator, in two years a 6 GeV continuous beam will be available. The maximum current is $200\mu A$, allowing very high luminosity experiments. At Hall C, is currently taking data for experiments, while Hall A and B are under the commissioning phase and will soon start their planned physics program.

The study of strangeness production will be investigated in all the three halls where, due to the complementarity of the experimental setup¹, different reactions, as well as different kinematical regions, will be explored.

The Hall A is a 53 m diameter circular experimental area equipped with a pair of High Resolution Spectrometers allowing high resolution (10^{-4}) detection of electrons and hadrons with a maximum momentum of 4 GeV/c. These focusing twin spectrometers are 45 deg vertical bending systems composed by two quadrupoles, one dipole and one more quadrupole magnet (QQDQ) along the 25 meters flight path of the travelling particles. The momentum and angular acceptances are 10% and 7.0 msr, respectively.

The focal plane detection system has tracking capabilities, hodoscopes to provide fast trigger, and a system of two Cherenkov counters used for particle identification, one with CO_2 gas as active material and one with aerogel.

The Hall C experimental setup is similar to that of Hall A, being equipped with two magnetic spectrometers, as well. In this case, however, an "asymmetric" pair of spectrometers was chosen: one is able to detect particles up to 6 GeV/c (the High Momentum Spectrometer) with moderate resolution ($\delta p/p \sim 5 \times 10^{-3}$), the other one has a short flight path (the Short Orbit Spectrometer) being mainly conceived to detect decaying particles (such as kaons) with maximum momenta of 1.8 GeV/c.

Hence, both Hall A and C are well suited to carry out high luminosity ($\sim 10^{37} cm^{-2} s^{-1}$) coincidence ($e, e' K^+$) experiments (of associated production of K - $Hyperon$ pairs) detecting in the final state the scattered electron and the produced kaon. While in Hall C this reaction can be well investigated at low and moderate energies (due to limitations on the highest measurable kaon momentum), Hall A is more suited to detect kaons of high momenta whose longer life time compensate for the longest flight path of the HRS spectrometer with respect to SOS.

The detector assembly of the Hall B is conceptually different. The Cebaf Large Acceptance Spectrometer (CLAS) is employed to detect (at lower luminosity, $\leq 10^{34} cm^{-2} s^{-1}$) multiple particles in the final state. It is composed by a toroidal magnet optimized to track from 8 to 140 degrees charged particle of momenta between 250 MeV/c and 4 GeV/c. An electromagnetic calorimeter and a gas Cherenkov detector provide electron, photon and π^0 detection for angles below 45° . The particle identification capability limit the strangeness production experiment to kaon momenta lower than 2 GeV/c.

A real photon beam is also available in Hall B where a photon tagging system operates from 20% to 95% of the bremsstrahlung endpoint energy, with about 5 MeV energy resolution.

In the following sections we will describe the theoretical framework and the models that can be adopted to investigate the strangeness production process. Then, we will outline those experiments aiming to investigate the elementary mechanism of the associated production of kaon-hyperon pairs, on nucleons,

induced by electron and by real photon beams.

Due to limitations of space, the present review could not fully treat the experimental program on kaon production at Jefferson Lab. Instead of going through a quick review of all the experiments (perhaps resulting only in a list of them) our choice was to focus on few (relevant in our opinion) subjects. Thus, we apologize to all of the authors who are going to contribute to this field of physics at JLab and have not been properly honoured in this paper.

2 The $(e, e' K^+)$ electro-production reaction - The elementary process on protons.

In order to write the cross section of the $(e, e' K^+)$ reaction and discuss the physics, let us introduce the appropriate variables². We will consider the exclusive channel of the Λ Hyperon production associated to the kaon in the $e + p \rightarrow e' + K^+ + \Lambda$ reaction, with a straightforward extension to other channels (i.e. Σ Hyperon production, or semiexclusive 'X' production). The 4-momenta that are directly measured in the reaction are e, e', P, k (related to the incident electron, the scattered electron, the proton target at rest in the lab. and the knocked-out kaon, respectively) while P_Λ (Λ 4-momentum) is determined by the conservation laws.

The following Lorentz invariant, related to the $\gamma^* + p \rightarrow K^+ + \Lambda$ virtual photo-production binary process can be defined:

$$\begin{aligned}
 q^2 &= (e - e')^2 = -Q^2 && \text{squared 4-momentum transfer} \\
 s &= (q + P)^2 = (k + P_\Lambda)^2 = W^2 && \text{squared invariant mass of the } \gamma^* \text{-} N \text{ system} \\
 t &= (q - k)^2 = (P_\Lambda - P)^2 && \text{squared momentum transferred to the hadronic system} \\
 u &= (q - P_\Lambda)^2 = (k - P)^2
 \end{aligned}$$

being s, t and u the Mandelstam variables.

Of particular note is the variable t which can be thought of as the momentum transferred to the remnant hadronic system, playing the same role in the (γ^*, K^+) virtual-photo-production reaction as that played by q^2 in the (e, e') inclusive experiments.

The electro-production cross section can be expressed in terms of the $\gamma^* + p \rightarrow K^+ + \Lambda$ cross section as:

$$\frac{d^5\sigma}{dE'_e d\Omega_e d\Omega_k} = \Gamma \frac{d\sigma(\gamma^*, k)}{d\Omega_k} \quad (1)$$

where Γ is the virtual photon flux.

In turn the virtual-photo-production cross section can be expressed in terms of 4 response functions:

$$\frac{d\sigma}{d\Omega_k} = \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \cos 2\Phi + \sqrt{2\varepsilon_L(\varepsilon + 1)} \sigma_{LT} \cos \Phi \quad (2)$$

where:

$$\varepsilon = \frac{1}{1 + 2|\vec{q}|^2/Q^2 \tan^2 \vartheta_e/2} \quad \text{and} \quad \varepsilon_L = \frac{Q^2}{\omega^2} \varepsilon$$

are the transverse and the longitudinal photon polarization, respectively, and Φ , in formula (2), is the "out of plane" angle that is the angle between the leptonic plane (defined by the incoming and outgoing electrons) and the reaction plane (defined by the direction of the 3-momentum transfer and that of the kaon).

The pieces correspond to the cross section for transverse (σ_T), longitudinal (σ_L), transverse interference (σ_{TT}) and longitudinal-transverse interference (σ_{LT}) kaon production by virtual photons and they only depend on the variables Q^2 , W (or s) and t .

In order to separate all the four pieces of the cross section, out-of-plane detection capabilities are needed to determine the Φ dependence of the cross section. In Hall B, the CLAS detector allows in principle to determine such a Φ distribution. However the separation of the response functions is a challenging goal in this case, since very good measurements accuracy, at the limit of CLAS possibilities, are needed. With two coplanar spectrometers, only when the kaon is detected along the direction of the virtual photon the interference terms vanish, and σ_L and σ_T can be separated using at least two measurements at different values of ε .

3 Theoretical models

To calculate the cross section of the process under investigation, different approaches can be adopted. In principle it could be calculated within the QCD theory making use of quark hadronization models. At CEBAF energies, however, non perturbative QCD degrees of freedom have to be taken into account. A more reliable approach in this case, is based on hadronic field theories (Quantum Hadron Dynamics) and makes use of semiphenomenological diagrammatic models where the explicit degrees of freedom are mesons and baryons and the tree level Feynman diagrams reported in figure 1 can be calculated.

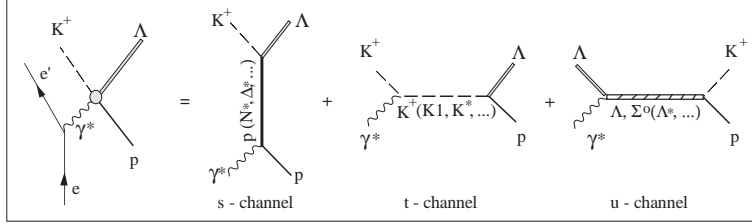


Figure 1: Tree level Feynman diagrams for the process $p(\gamma^*, K^+)\Lambda$

Contributions to the cross section from these diagrams are usually calculated in a semiphenomenological way, trying to fit the unknown parameters to the existing data. One of the main problems encountered in this kind of approach is the determination of the proper set of particles as propagators (p, K^+, Λ, Σ are Born terms). Moreover, in the fitting procedure, the values of the coupling constants (like the leading coupling constant $g_{K\Lambda N}$) have also to be established. So far, quite a large variety of models, in this framework, have been developed (see e.g. ref.²), but, at present, with the available photo production data (collected e.g. in ref.³) and electro-production data (collected e.g. in ref.⁴) it is not possible to determine unambiguously a given set of propagators and coupling constants. Due to the lack of high quality experimental data in a wide kinematical region, different models, taking into account very different set of diagrams and parameters, are able to satisfactorily reproduce most of the data. On the other hand, they give very different predictions in those regions where a comparison with the data is not possible yet. Thus, the situation has to be clarified and a consistent data set in a broad kinematical range is needed.

At CEBAF energies of 6 GeV (and maybe even more, in the next future) the transition into the hard scattering regime could be explored. Thus, the reliability of different models, based on perturbative QCD or phenomenologically inspired to QCD, can be tested.

In the region where non perturbative effects are still present, an approach based on the idea of diquark can be appropriate and promising. Recently, theoretical predictions of exclusive photo- and electro-production of kaons based on QCD semiphenomenological diquark models have become available⁵

The main ingredients of the diquark model are: *i*) baryon treated as quark-diquark systems; *ii*) phenomenological diquark form factors taking into account the composite nature of diquarks; *iii*) the gluons and photons couplings to diquarks.

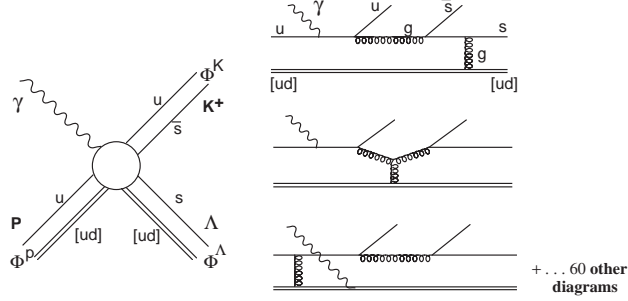


Figure 2: A few representative examples of diagrams contributing to the process $\gamma u[ud] \rightarrow u\bar{s}s[ud]$

In its ground state a diquark has positive parity and may be an axial-vector (spin 1) or a scalar (spin 0) boson. The baryon wave function can be written as

$$\Psi^B(p, \lambda) = f_S \Phi_S^B(x_1) \chi_S^B u(p, \lambda) + f_V \Phi_V^B(x_1) \chi_V^B \frac{1}{\sqrt{3}} (\gamma^\alpha + p^\alpha/m_B) \gamma_5 u(p, \lambda) \quad (3)$$

where the two terms represent configurations consisting of a quark and either a scalar (subscript S) or vector (subscript V) diquark and:

- i) Φ^B are the baryon distribution amplitudes, the valence Fock-state (consisting of a quark and a diquark) wave functions integrated over the transverse momentum. The argument x_1 is the momentum fraction of the parent baryon carried by the quark ($p_q = x_1 p_B$). It is assumed (collinear approximation) that it sums up to 1 with the momentum fraction of the diquark ($p_D = x_2 p_B = (1 - x_1) p_B$)
- ii) f are the $r = 0$ values of the distribution amplitudes
- iii) χ are the flavour functions and $u(p, \lambda)$ are spinors with helicity λ .

Investigating the $\gamma^{(*)} + p \rightarrow K^+ + \Lambda$ reaction, the hard scattering amplitude can be calculated perturbatively taking into account all the possible tree diagrams contributing to the elementary scattering process $\gamma u D \rightarrow u\bar{s}s D$ where D is a u - d diquark. In figure 2, only few diagrams are reported as an example, together with a blob representation of the process.

The flavour functions $\chi_{S,V}^{p,\Lambda}$ for the proton and the lambda hyperon take on the form :

$$\chi_S^p = uS_{[u,d]} \quad , \quad \chi_V^p = [uV_{\{u,d\}} - \sqrt{2}dV_{\{u,u\}}] \quad (4)$$

$$\chi_S^\Lambda = [uS_{[d,s]} - dS_{[u,s]} - 2sS_{[u,d]}]/\sqrt{6} \quad , \quad \chi_V^\Lambda = [uV_{\{d,s\}} - dV_{\{u,s\}}]/\sqrt{2} \quad (5)$$

The simplifying feature of the specific process under investigation is that only scalar diquarks contribute, since, from eqn. (4) and (5), only scalar diquarks $S_{[u,d]}$ are common to both the proton and the Λ (while for the exclusive channel $\gamma^{(*)} + p \rightarrow K^+ + \Sigma^0$ only the vector $V_{\{u,d\}}$ diquark contribute). As a consequence, the number of diagrams is reduced to 63 “only”. A physical consequence of that is the vanishing of the polarization of the produced Λ . Thus, the measurement of the Λ polarization, as well as the comparison of the Λ and Σ^0 production, turns to be very important.

4 The planned experimental program

In tables 1, 2, 3 the experiment on the subject of strangeness productions, planned at JLab, are listed.

At present, the experiment 94-108, proposed within a collaboration where our group is involved, is not yet fully approved. Fully approval is conditioned under the demonstration of the feasibility of Longitudinal-Transverse separation of exp. 93-018 which has now just taken data. Nevertheless in the following, we will refer to this experiment as well, since it exploits the unique possibility at Jlab to study the elementary process of exclusive kaon electro-production through the $(e, e'K^+)$ reaction on hydrogen target up to rather high values of the momentum transfer ($Q^2 \leq 3(GeV/c)^2$) and of the center of mass energy ($W = \sqrt{s} \leq 2.2GeV$).

4.1 Kaon electro-production experiments on proton target

The main goals of the kaon electro-production experiments $(e, e'K^+)$ are :

- The partial or total separation of the four terms of the cross section, $\sigma_L, \sigma_T, \sigma_{LT}, \sigma_{TT}$; their separate measurements generally provide a very stringent test of the models. As a matter of fact:

the longitudinal photons contributing to σ_L are sensitive to scalar particle exchange in the t -channel, hence sensitive to kaons as propagator particles, or, for example, to scalar diquarks. The possibility to measure, in addition, the kaon electromagnetic form factor from the t -dependence

Table 1: The elementary process for kaon electro-(photo)-production

electro-production experiments: $p(e, e' K^+) \Lambda, \Sigma, \dots$

| Exp n. | Hall | Title | Spokespersons |
|--------|------|--|---|
| 93-030 | B | Measurement of the Structure Functions for Kaon Electro-production | M.Mestayer, K.H.Hicks |
| 93-018 | C | Longitudinal/Transverse Cross Section Separation in $p(e, e' K^+) \Lambda, \Sigma$ for $0.5 < Q^2 < 2.0(GeV/c)^2$, $W > 1.7 GeV$, $t_{min} > 0.1(GeV/c)^2$ | O.K.Baker |
| 89-043 | B | Measurements of the electro-production of the $\Lambda(gnd)$, $\Lambda^*(1520)$ and $f_0(975)$ via $K^+ K^- p$ and $K^+ \pi^- p$ Final States | L.Dennis, H.Funsten |
| 94-108 | A | Electro-production of Kaons up to $Q^2 = 3(GeV/c)^2$ | O.K.Baker, C.C.Chang, S.Frullani, M.Iodice, P.Markowitz |
| 95-003 | B | Measurement of the K^0 electro-production | R.A.Magahiz |

photo-production experiments: $p(\gamma, K^+) \Lambda, \Sigma^0, \dots, p(\gamma, K^0) \Sigma^+$

| Exp n. | Hall | Title | Spokespersons |
|--------|------|--|---------------|
| 89-004 | B | Electromagnetic Production of Hyperons | R.Schumacher |
| 89-024 | B | Radiative Decays of the Low-Lying Hyperons | G.S.Mutchler |

Table 2: Kaon electro-(photo)-production on light nuclei

| Exp n. | Hall | Title | Spokespersons |
|--------|------|--|---------------|
| 89-045 | B | Study of the Kaon Photo-production on Deuterium | B.Meking |
| 91-016 | C | Electro-production of Kaons on Light Hypernuclei | B.Zeidman |

Table 3: Kaon electro-(photo)-production on heavier nuclei

| Exp n. | Hall | Title | Spokespersons |
|--------|------|--|---|
| 91-014 | B | Quasi-Free Strangeness Production in Nuclei | C.Hyde-Wright |
| 89-009 | C | Investigation of the Spin Dependence of the ΛN Effective Interaction in P Shell | R.Chrien, E.Hungerford, L.G.Tang |
| 94-107 | A | High Resolution 1p Shell Hypernuclear Spectroscopy (on ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$) | S.Frullani, F.Garibaldi, J.LeRose, P.Markowitz, T.Saito |
| 95-002 | C | Direct Measurement of the Lifetime of Heavy Hypernuclei at CEBAF | L.G.Tang, A.Margarian |

of the σ_L term, in the same way as what has been done in the past for the pion form factor, will be discussed later.

The longitudinal-transverse interference term is very sensitive to the different available models and could also give information on the magnitude of the transverse momentum of the quarks⁶.

- The measurement of the Λ/Σ production ratio. Since all the experiments have exclusive character, from the missing energy spectra the two reactions $e + p \rightarrow e' + K^+ + \Lambda$ and $e + p \rightarrow e' + K^+ + \Sigma^0$ can be disentangled. The different contribution of scalar and vector diquarks to the two reactions can therefore be investigated.
- The study of the t -dependence of the full cross section up to large values of $|t|$ and Q^2 . In this region, the transition from a semiphenomenological description in terms of mesons and baryons to a hard scattering regime in which the theoretical approach based on quarks or diquarks description of the elementary process is applicable.

Most of these goals constitute the expectations of experiment 94-108⁷. This experiment will place severe constraints on the models used to reproduce the data. In particular, important parameters such as the $g_{\Lambda N}$ coupling constant used in semi-phenomenological models based on hadron dynamics formalism, can be much better established. Additionally, the transition to a more

fundamental description of the reaction in terms of quarks can be identified. In common with exp. 93-018, in a complementary (highest) region of Q^2 , is the goal to study the problem of the determination of the kaon electromagnetic form factor from the t -dependence of the longitudinal cross section.

The kaon form factor

In the space-like region, the only existing measurements for the kaon form factor come from $k - e$ scattering⁸ and are limited to values of 4-momentum transfer $\leq 0.1(GeV/c)^2$. The possibility to determine the kaon form factor through the electro-production reaction, relies on the fact that the t -channel diagram of fig.1, in which the exchanged meson is the kaon (kaon pole diagram), dominates all the other diagrams in the chosen kinematic. If this is true, an extrapolation procedure has still to be carried out, as the probed kaon is not on mass shell, having t , its 4-momentum squared, a negative value.

The method chosen to maximize the t -channel contribution, while minimizing the s - and u -channel contributions is to examine the longitudinal response as a function of t , and to extrapolate to $t = m_k^2$, similar to what has been done in the case of the pion⁹. In such a way the kaon form factor comes from the following extrapolation:

$$F_k^2(Q^2) = F^2(Q^2, t)|_{t \rightarrow m_k^2} = \frac{(t - m_k^2)^2 \sigma_L}{N(t)}|_{t \rightarrow m_k^2} \quad (6)$$

where $N(t)$ is a known function of t .

Theoretical guidance would be necessary in the extrapolation to exploit model-independent constraints and analytical properties of the amplitudes. Without such theoretical indications and in the absence of the experimental data showing how much the kaon pole diagram contributes to the longitudinal cross section, it is very difficult and risky to face an analysis of uncertainties in the extraction of the kaon form factor. However, in order to understand in some detail the problem, we have estimated the uncertainties from a linear fit, extrapolated to the kaon pole, of the function $(t - m_k^2)^2 \sigma_L / N(t) = F^2(Q^2, t)$. Such a function has been calculated on the basis of particular models and the projected statistical errors on the extracted longitudinal terms have also been taken into account. In this procedure, we also made a self-consistency test by checking that the obtained values of the form factor were consistent with those used by the model itself⁷. This exercise was made in the framework of the "wjc4" model¹⁰. The results obtained for $Q^2 F_k(Q^2)$ have been reported in figure 3 as projected measurements at CEBAF. Also shown are other simpler

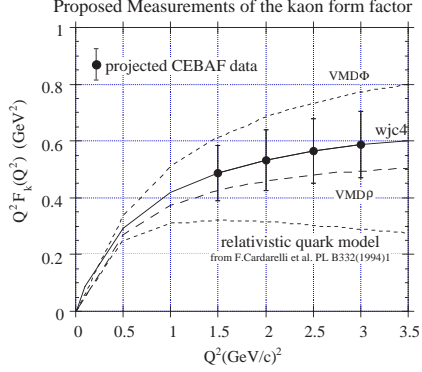


Figure 3: Measurements of the kaon form factor. Shown are the four points of the proposed experiment together with the projected experimental uncertainties. For the theoretical curves see the text.

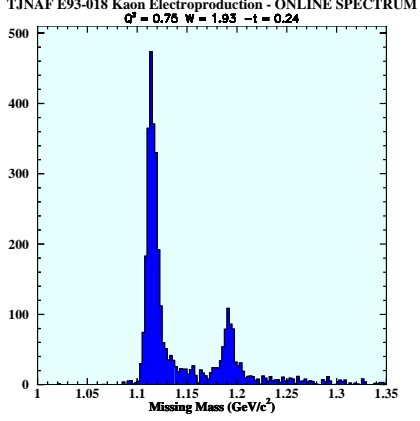


Figure 4: ON-LINE (preliminary) missing energy spectrum of the $p(e, e' K^+)$ 93-018 experiment. The two reaction channels $p(e, e' K^+) \Lambda$ (first peak) and $p(e, e' K^+) \Sigma^0$ (second peak) are clearly distinguishable. The beam energy was 4.045 GeV .

Vector Mesons Dominance Model predictions which consider the Φ and ρ -mesons and predictions from a model based on a more fundamental approach¹¹.

Initial studies of kaon electro-production have been completed at CEBAF. The measurements included angular and momentum transfer dependences of the $(e, e' K^+)$ reaction in hydrogen, deuterium, and carbon nuclei. A very preliminary (almost on-line) example of how the missing energy spectrum looks like, with the clear identification of the two channels $K^+ - \Lambda$ and $K^+ - \Sigma^0$, is reported in figure 4.

4.2 Kaon photo-production experiments on proton target

Important complementary information for the studies of the elementary electromagnetic production of kaons come from the photo-production experiments planned for the Hall B with the use of the CLAS detector.

The main goals of these experiments are :

i) investigation of the three reaction channels:

$$\gamma + p \rightarrow K^+ + \Lambda, \quad \gamma + p \rightarrow K^+ + \Sigma^0, \quad \gamma + p \rightarrow K^0 + \Sigma^+$$

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