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Associated Strangeness Production at Intermediate Energies

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Abstract

Elementary strangeness production reactions with hadronic and electromagnetic probes are briefly reviewed. Some recent theoretical and experimental findings are underlined and a few open questions are singled out.

1 Introduction

The strangeness tale started roughly half a century ago and we have not yet discovered entirely this wonderland. To my knowledge, the story goes back to December 1944 with a communication by Leprince-Ringuet and Lhéritier [1] to the French Academy of Sciences. The authors reported on the observation of a positively charged particle that gave a δ-ray in a cloud chamber the mass of which was determined to be $(990 \pm 119)m_e$, hence compatible with the, by now well known, K^+ mass. However, this positively charged particle was taken by the community as a mismeasured proton.

This unfortunate skepticism has probably at least two origins. First, the general wisdom at those days was in the economy of particles and not, as later, in the invention of a new one at the first sign of a slight bump. Second, the fact that the fundamental particle predicted by Yukawa [2] had been mistakenly thought to have been discovered. Moreover, the observed particle (the muon) [3] had given rise to more problems than bringing any answer to the nature of the mediating force of strong interactions.

Actually, the first paper [4] on the discovery of the true Yukawa particle (the pion) appeared in February 1947. The identification of the pion was confirmed [5] in May 1947 and evidence for clear distinction [6] between the pion and the muon was released in October of the same year. Hence, in December 1947, when Rochester and Butler [7] published their results on two examples of "forked tracks" observed in a Cosmic Ray cloud chamber experiment, corresponding to particles with masses close to $1000m_e$, the community was in a better mood than three years earlier to consider eventual existence of new particles. These data contained two events corresponding to the production of, as now called, K^0 and K^+ which decayed to charged particles. The traces of the final decay particles in cloud chamber were "*V*" shaped, and hence they were named "V particle". The reactions involved $\pi^- p$ in the initial state, with supposedly strong interactions as production mechanism.

-Assumption that the produced unstable particles decayed also via strong interactions led to a real puzzle: the decay constants inferred from the data were 10^{12} times lower than the expected values. This fact implied that the production and decay processes involved different particles and forces, introducing [8] hence the idea of the associated production of these new particles. This hypothesis was soon confirmed experimentally [9] due to the measurements at the cosmotron at Brookhaven producing much more copious data than was the case with Cosmic Rays measurements. This experiment brought also clear evidence on the strong interaction nature of the strangeness production.

Generalizing the charge independence hypothesis, Gell-Mann [10] and Nishijima [11] independently conceptualized the whole subject by introducing a new additive quantum number called, by Gell-Mann, Strangeness; seemingly conserved in strong but not in weak interactions. This crucial step led in late 50s to the SU(3)-symmetry classification [12] of the hadrons. Finally these efforts culminated in early 60s by the advent of subnucleonic particles scheme [13] called, again by Gell-Mann, quarks.

In spite of such a tight connection between the strangeness and the compositeness nature of the hadrons, and as we will see in the following sections, our most reliable understanding of the strangeness physics at intermediate energies is based at the present time, on the nucleonic and mesonic degrees of freedom.

Ln the next three sections, we survey briefly associated strangeness production via hadronic (protons and kaons) & electromagnetic (electrons and photons) probes with incidents energies up to 3 GeV.

2 Nucleon-Nucleon Interactions

The main field of interest in intermediate energy baryon-baryon interactions has involved nucleon-nucleon (NN) systems as well as the behavior of the first baryonic resonance Δ_{33}, where at the subnucleonic level only *u*- and d-quarks intervene. The quantum number of strangeness brought about by the s-quark implies the investigation of hyperom-nucleon (YN) and hyperon-hyperon interactions, production and propagation of hyperonic resonances, and strangeness exchange mechanisms. In the absence of intense enough hyperonic bearns, strangeness production with hadrons, e.g., pp --> KYN, as well M the reactions with the incident photons or electrons as discussed in the next sections, offer an attractive alternative to investigate these quests.

After the pioneer works [14] in early 70s, on the YN interactions based on one boson *exchange* approaches two elaborated potentials have been developed: *Nijmegen* soft core potential [15], and Bonn-Jülich potential [16]. These models have the extra advantage of offering unified approaches to NN and YN interactions. In contrast to the NN case, in the ΛN system the exchanges of single π and ρ are forbidden because of the isospin conservation, while the exchanges of single K and K* are required. Although the NN pair can exist in bound state, there is no clear experimental evidence for the existence of ΛN nor ΣN dibaryons (neither for the exotic KN) states (Table 1).

Table 1: Proton-proton collision processes [17] with effective intermediate two body states; namely, dibaryons and exotics containing s and $\bar{s}$ valence quarks, respectively.

initial state		effective two body intermediate state		intermediate state		final state
$p\,p$	$\rightarrow$	$[N^*]p$	$\equiv$	$[K^+\Lambda]p$	$\rightarrow$	$K^+\Lambda p$
	$\rightarrow$	$[Dibaryon]K^+$	$\equiv$	$[\Lambda p]K^+$	$\rightarrow$	$K^+\Lambda p$
	$\rightarrow$	$[Exotic]\Lambda$	$\equiv$	$[K^+p]\Lambda$	$\rightarrow$	$K^+\Lambda p$

However, in bubble chamber experiments, two narrow peaks in the missing mass spectrum of the YN system around the ΣN production threshold have been observed in the

$K^- d$ and $\pi^- d$ collisions [18]. The first peak is likely due to a cusp effect because of opening of the $\Sigma^+ n$ and $\Sigma^\circ p$ channels, while the second one might be considered as a candidate for one of two low-lying strange dibaryons predicted by several authors [19] and based the MIT bag-model [20] . However, older data obtained at BNL [2 1] and using magnetic spectrometers show no structure near the ΣN threshold.

As mentioned above, in addition to mesons another hadronic probe can be used to investigate the above subjects *via* the following reactions

$$p\, p \;\rightarrow\; K^+ \Lambda p\ ,\ K^+ \Sigma^\circ p\ ,\ K^+ \Sigma^+ n. \qquad (1)$$

This unclear situation motivated hence the first $p(p, K^+)X$ high statistics and high resolution measurements at SATURNE by R. Siebert et *al. [22] . In* this experiment, a liquid hydrogen target was used and the differential cross sections of the reaction pp --> K^+X were investigated at two proton beam energies, 2.3 and 2.7 GeV, with outgoing kaons detected at forward angles up to 23.5° using SPES4.

Two recent models [23, 24] based on one boson exchange approaches reproduce well enough the data below the ΣN threshold. Above, there are significant discrepancies between models and data presumably due to some missing interference terms in the theory. The most striking features of these data are related to three enhancements and/or structures. The enhancement at the missing mass of 2131 ± 1.5 MeV, is observed at $T_p^{lab} = 2.3$ GeV. While this cusp effect vanishes at higher negative momentum transfers, a new structure appears at $T_p^{lab} = 2.7$ GeV and $\theta_{kaon}^{lab} = 20^\circ$, centered at 2136 ± 2 MeV with a width of 16 MeV, corresponding to a possible strange dibaryon [19]. Finally a third, less pronounced, structure at 2098 ± 1.5 MeV is attributed [22] to statistical fluctuations.

A quantitative progress in this field requires exclusive measurement with access to the polarization observable. Such measurements been proposed [25, 26] at *SATURNE.* The first proposal, by DISTO [25] collaboration is an experiment in progress and focuses on the measurement of the differential cross section of the reactions pp --> K^+Yp; with $Y \equiv \Lambda, \Sigma^\circ$. Moreover, a polarized beam will be used and the polarization of the produced Λ is also planned to be measured. The second proposal [26] concerned also the exclusive measurement of the reaction $\vec{p}p \rightarrow K^+\vec{\Lambda}p$ in almost the whole phase space (unfortunately, this project could not overcome technocratic barriers and hence, never got started,)

At the new COSY facility [27] several groups [28] are involved in the strangeness physics with proton beams. The forthcoming data are awaited for to pursue several of the interesting issues in this realm.

3 Kaon-Nucleon Low Energy Interactions

The interest in the K^--proton interactions [29] is characterized by the fact that even at low energies the K^- *can* scatter from the proton not only elastically but also go through inelastic channels; namely:

$$K^-\, p \;\rightarrow\; K^- p\ ,\ \overline{K^0} n\ ,\ \Sigma^+\pi^-\ ,\ \Sigma^0\pi^0\ ,\ \Sigma^-\pi^+\ ,\ \Lambda\pi^0\ ,\ \Lambda\gamma\ ,\ \Sigma^\circ\gamma. \qquad (2)$$

Investimating the K--proton system, implies hence studying simultaneously all the above eight processes.

One of the main efforts in this field is focused on the understanding the nature of the $\Lambda(1405)$ resonance (which lies just below the K^-p threshold at 1432 MeV): an s-channel resonance [30], a quasi-bound ($K-N, \Sigma\pi$) state [31-34], a pure q^3 state [35], a quasi-bound $\overline{K}N$ state [36], a hybrid ($q^3+q^4\overline{q}...$) state [37], an "elementary" field [38], composed by an SU(2) soliton and a kaon bound in a S-wave [39].

Besides, the amplitudes of the two radiative capture reactions can be related, via crossing symmetry, to those of the strangeness photoproduction $\gamma p \rightarrow K^+\Lambda(K^+\Sigma^0)$, discussed in the next section.

Close to threshold (*i.e.* p_K^{lab} < 200 MeV/c), in addition to roughly 70 total cross section data points 40] for the six strong processes, accurate threshold branching ratios data are also availabe [41, 42], i.e.,

$$\gamma = \Gamma(K^-p \rightarrow \pi^+\Sigma^-)/\Gamma(K^-p \rightarrow \pi^-\Sigma^+) = 2.36 \pm .04, \quad (3)$$

$$R_c = \Gamma(K^-p \rightarrow charged\ particles)/\Gamma(K^-p \rightarrow all) = .664 \pm .011, \quad (4)$$

$$R_n = \Gamma(K^-p \rightarrow \pi^0\Lambda)/\Gamma(K^-p \rightarrow\ all\ neutral\ states) = .189 \pm .015, \quad (5)$$

$$R_{\Lambda\gamma} = \Gamma(K^-p \rightarrow \Lambda\gamma)/\Gamma(K^-p \rightarrow all) = (.86 \pm .07 \pm .09) \times 10^{-3}\ , \quad (6)$$

$$R_{\Sigma\gamma} = \Gamma(K^-p \rightarrow \Sigma^0\gamma)/\Gamma(K^-p \rightarrow all) = (1.44 \pm .20 \pm .11) \times 10^{-3}. \quad (7)$$

The existing data put hence tight constraints on the threshold amplitudes and coupling strengths. Recently all the low energy data have been well reproduced (Tables 2 & 3) within a *single model [34]* using a general coupled-channel formalism, where the Λ(1405) is produced as a K – $N(\Sigma\pi)$ bound state resonance.

Table 2: *K-p* threshold strong branching ratios

author [Ref.]	γ	R_c	R_n
Siegel-Saghai [34]	2.31	.661	.164
EXPERIMENT [41]	2.36 ± .04	.664 ± .011	.189 ± .015

One of the most striking features comes from the drastical dependence of these branching ratios on the initial state interactions (ISI). Results for the *K-p* threshold radiative capture branching ratios from four different formalisms are summarized in Table 3. Among the coupled channel calculations, only results reported in Ref [34] reproduce well enough the data, while those by Zhong et al. [36] are too high roughly by a factor of 2, and the Tanaka-Suzuki potential [33] misses [34] by far the data. Another approach, based on diagrammatic techniques and discussed in the next section, has also been applied by David et *al.* [43] to these channels giving good agreement with the data. Table 3 also shows

Table 3: *K-p* threshold radiative capture branching ratios. The initial state interactions effect in the Tanaka & Suzuki potential are reported in Ref.[34]. .

Authors [Ref.]	$R_{\Lambda\gamma} \times 10^3$	$R_{\Sigma\gamma} \times 10^3$	Formalism
Tanaka & Suzuki [33]	17.5	3.29	*coupled-channel* with ISI
Siegel-Saghai [34]	1.09	1.55	*coupled-channel* with ISI
Siegel-Saghai [34]	0.56	0.12	*coupled-channel* without ISI
Zhong *et al.* [36]	1.90	2.30	*coupled-channel* with ISI
David *et al.* [43]	0.95	1.44	*Diagrammatic technique*
EXPERIMENT [42]	.86 ± .12	1.44 ± .20	

that if the initial state interactions are switched off, the ratios $R_{\Lambda\gamma}$ and $R_{\Sigma\gamma}$ decrease by roughly a factor of 2 and more than one order of magnitude, respectively.

It is also interesting that at threshold $R_{\Lambda\gamma}$ is substantially less than $R_{\Sigma\gamma}$. The most comprehensive investigation [34] shows that this trend is general at energies below the $\overline{K^0}n$ threshold, while at higher energies the ratio $R_{\Lambda\gamma}$ becomes greater than $R_{\Sigma\gamma}$. Experimental data of these branching ratios at low energies with kaons in flight would hence help clarify the nature of the $\Lambda(1405)$.

Another puzzling aspect concerns the *K-p* scattering length. While most of the theoretical investigations produce a negative sing for this scattering length (Table 4), from the existing data [44] on the 1s atomic level shift it is generally inferred that this sign is positive.

Table 4: *K-p* scattering length

Authors [Ref]	a_{K^-p} (fm)	*1s* atomic level shift
Siegel-Saghai [34]	− 0.63 + 0.76 i	*not fitted*
Martin [47]	− 0.66 + 0.64 i	*not fitted*
Tanaka & Suzuki [33]	− 1.11 + 0.70 i	*not fitted*
Tanaka & Suzuki [33]	+ 0.34 + 0.77 i	*fitted*

Nevertheless, these data suffer from lack of accuracy and even the values within quoted error bars seem questionable [45]. Recent results [34] tend to show that reproducing *simultaneously* the measured electromagnetic branching ratios with high accuracy and a positive scattering length can not be achieved with the present approaches (see Tables 3 & 4). New and accurate masurements of the kaonic atoms level shifts are hence highly desirable. Such measurements are underway, or planned, at BNVL, KEK, and DAPHNE.

4 Electromagnetic production

Another appealing alternative to study strangeness physics is using electromagnetic probes. The advent of high quality polarized electron and/or photon beams at CEBAF, *ELSA*, and *ESRF* has restored and strengthened **a** dormant field. Such a promising future has revivaled theoretical investigations in this field.

Besides the consideration of crossing symmetry which connects investigations with kaonic probes and those utilizing electromagnetic probes, a few long lasting problems have been, or are being, solved.

Here, the most advanced theoretical frame [43] is based on an effective Lagrangians approach in the tree approximation. Through this formalism the following reactions are studied simultaneously

$$\gamma\, p \rightarrow K^+\Lambda\ ;\ K^+\Sigma^\circ\ ,\ K^\circ\Sigma^+; \tag{8}$$

$$e\, p\ \rightarrow\ e'K^+\Lambda\ ,\ e'K^+\Sigma^\circ; \tag{9}$$

$$K^-\, p\ \rightarrow\ \gamma\Lambda\ ,\ \gamma\Sigma^\circ. \tag{10}$$

The relevant Feynman diagrams, include a large number of possible exchanged particles in the s- , *u*-, and t-cha.rinels. These channels correspond to different families of resonances: nucleonic (spin $\leq 5/2$), hyperonic (spin = 1/2), and $K^*(896)$ & $K1(1270)$, respectively.

Within such a phenomenological approach, a *priori* some 25 exchanged resonances can intervene. Moreover the relevant coupling constants. for both Born and resonant terms are in general not known and constitute the free parameters in the phenomenological approaches. Notice that the main coupling constants $g_{KN\Lambda}$ and $g_{KN\Sigma}$ can be related [46] to the rather well known $g_{\pi NN}$ coupling *via* SU(3) and SU(6) symmetries. Extracted values of these couplings from hadronic sector [47] agrees with the broken SU(3)-symmetry predictions [48]. Nevertheless, for more than two decades the values determined from electromagnetic production side were too far from their SU(3) values. This puzzle is by now solved [48]. Moreover, a recent model independent approach [49] proved to be conclusiive [50] in constraining the number of exchanged resonances in the reaction mechanism.

Production of strangeness from deuteron [51] allows to study the elementary processes on the neutron. Moreover, they offer a clean system to investigate the hyperon-nucleon interactions in the final state via the following reactions:

$$\gamma\, d \rightarrow K^+\Lambda n,\ K^+\Sigma^\circ n,\ K^\circ\Sigma^+ n\ ;\ K^+\Sigma^- p\ ,\ K^\circ\Lambda p,\ K^\circ\Sigma^\circ p \tag{11}$$

Copious and much precise phot- and electro-production data, including single and double polarization measurements, are expected in the near future from *CEBAF*, *ELSA*, and *ESRF*.

5 Concluding Remarks

Intermediate energy strangeness physics explored by elementary particle physicists till mid-seventies, has become one of the main fields of interest in hadronic physics. With the recent advent of several high quality facilities, this physics is being extensively investigated with different probes. New data becoming available, or foreseen in the near future, have motivated intense theoretical studies through a large spectrum of formalisms based on different concepts. Such a diversity of "tools" and approaches will certainly contribute very significantly to our understanding of the role of strangeness in the nature.

One of the promising novelties in this field is due to important technical achievements allowing accurate measurements of polarization observable. Here, strangeness production processes are self-analyzing; e.g. the angular asymmetry in the parity non conserving weak decay $\Lambda \rightarrow \pi N$ provides a direct measurement of the Λ's polarization; also $\Sigma^\circ \rightarrow \Lambda\gamma$ and so on. This topic, not reviewed here because of space limitations, offers [52] a fine probe to the composite structure of the strange particles and the reaction mechanisms.

Processes induced by hadronic probes are called upon to resolve several fundamental still open problems raised by the strange quarks, e.g.,

- Achieve a more quantitative description of the hyperon-nucleon interactions.
- Search for strange dibaryon and exotic states.
- Understand the nature of hyperonic resonances such as $\Lambda(1405)$.
- Determine whether the KN interaction is attractive or repulsive.

Electromagnetic probes open new areas in this field and bring complementary insights to some crucial issues of the strangeness physics, e.g.,

- Provide a better and more realistic understanding of the reaction mechanisms of the elementary processes on the nucleon. This should allow a better determination of the fundamental coupling constants, especially $g_{K\Lambda N}$ and $g_{K\Sigma N}$, providing hence complementary information on the structure of the vacuum [54].

. Clear up the validity of the duality hypothesis in the strangeness sector [50].

- Using nodal structure approach [49, 50], search for missing and undiscovered baryonic resonances [.53] as predicted by QCD based approaches [5.5].

- Examine carefully the interplay between effective Lagrangians approaches based on the mesonic and baryonic degrees of freedom [43] and the QCD inspired formalisms [56] and establish links between the two schemes.

- Investigate the electromagnetic form factors of the hadrons and especially the form factors of hyperons and kaons including the relevant hadronic resonances [43, 57]. Recent developments in this field, based on the QCD approaches [58], appear very promising.

- Use the elementary operators to deepen our understanding of the hypenuclei physics [59] by studying not only natural parity hypernuclei states (as in the case of hadronic probes) but also the unnatural parity states. Other important issues will also be addressed: by studying the modifications of the static properties of the hyperons in the nuclear medium find out whether there is a strange EMC effect; establish wheteher the A inside a hypenucleus is governed by the Pauli principle (at the quark level the answer to this question is unclear).

By the end of this century, very significant progress on these questions, and many others, are expected due to the conjugate outcome of intense theoretical investigations **and the** forthcoming data from several laboratories: *BNL, CEBAF, COSY, DAPHNE, ELSA, ESRF, KEK,* and *SATURNE.*

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