Experimental issues on $K^-$ absorption by few nucleons and the search for Bound Kaonic Nuclear Systems

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Abstract. The available experimental data on $K^-$ absorption on nuclei are rather old and scarce and cannot help very much to understand whether the formation of composite objects made by kaons and many nucleons can occur. The existence of such structures is suggested by a few theoretical models, but many others do not expect them – or at least consider their experimental observation very difficult. The experimental study of their existence is based on the observation of hyperon-nucleon correlations, and on the features of the $\Lambda p(d,t)$ invariant mass distributions. If existing, in fact, these aggregates should non-mesonically decay in hyperon-nucleons final states, being the pionic channels forbidden due to energy conservation. Complementary information may also be gathered by the study of missing mass distributions.

Recent experiments restarted the study of $K^-A$ absorption in light nuclei, namely on $^4$He by KEK-E549, and on $^6,^7$Li, $^9$Be and $^{12}$C by FINUDA at DAΦNE.

The experimental results obtained so far by the various experiments studying the $K^-$ absorption in nuclei are here summarized and presented.

Keywords: Kaon absorption; Kaonic nuclear bound clusters

$K^-$ ABSORPTION: GENERAL OVERVIEW

Information on the $K^-$ interaction on nucleons can be obtained by measuring the particles emitted in absorption processes in nuclei. Usually the $K^-$ is absorbed in the nuclear periphery, thus the process depends on the nuclear density in the tail region and on the Fermi motion of the hit nucleons. These features must be properly taken into account to fully understand the $K^-$ capture mechanism.

Data on the absorption processes undergone by a $K^-$ interacting with a nucleus are however few and rather old, dating back to bubble chamber experiments [1, 2]. The existing database is rather sparse and only recently it has been revitalized by the new data collected by experiments at KEK and LNF. The interest on the $K^-$ absorption phenomena lies in the possible interplay they could have with the formation of bound kaonic systems, few-body strange aggregates formed by nucleons and an antikaon. Their existence was firstly suggested by Akaishi and Yamazaki [3]; their experimental search is presently actively pursued, and constitutes a research object of future planned experiment, in spite of the absence of a general consensus from the theoretical point of view on their existence or, at least, their observability [4, 5, 6, 7].

The $K^-$ absorption by a single nucleon leads to the production of a slow hyperon and a pion (quasi-free reaction $K^-N \rightarrow Y\pi$), and is the basic mechanism for the hypernuclear production. On the other hand, in order to form a bound kaon-nuclear cluster, whose binding energy is supposed to be as large (~110 MeV/c) as to prevent its possible decay in the $\Sigma\pi$ channel, the interaction must occur on two or more nucleons, without pion emission ($K^- (2N) \rightarrow YN, K^- (3N) \rightarrow Y(NN), K^- (4N) \rightarrow Y(NNN)$). The nuclear-kaonic system can be therefore considered as an intermediate step occurring in the many-nucleon absorption of a $K^-$, undergoing a non-mesonic decay in a pionless final state composed by a hyperon (typically a $\Lambda$) and nucleons or light nuclei (i.e. deuterons and tritons).

The hyperon emitted in a multinucleon kaon absorption has a rather large momentum (> 500 MeV/c), which would allow a clear separation of this reaction from the kaon absorption by a single nucleon. First bubble chamber experiments measured the semi-inclusive production rate of hyperons in pionless final states only on $^4$He [1], reporting around 12% (per $K^-_{top}$) for the non-mesonic production of $\Lambda$ (and $\Sigma^0$), and respectively 1% and 3.6% for the non-mesonic production of $\Sigma^+$ and $\Sigma^-$. Semi-inclusive non-mesonic rates were also deduced for heavier targets [2], and in general a linear dependence with $A$ was found, with values as large as 15-30% in nuclear emulsions.

Old experiments unfortunately were not able to add much more information on the absorption mechanisms, due
to the small available statistics and worse momentum resolution when high momentum particles were involved. Usually their final issues were given in the form of inclusive or semi-inclusive momentum spectra. To this purpose, complete spectrometers should on the contrary be used, able to provide full topologic and kinematic information of the absorption event. Only recently new experiments were performed with these features.

KEK-E549 performed a high statistics \( K^- \) to 4He absorption experiment [8, 9] and was able to effectively separate, by means of the missing mass method, several reactions contributing to the observed \((\Lambda N)\) final state. While the \( K^- \) to 4He \( \to \Sigma(3N) \) followed by \( \Sigma \) conversion and \( K^- \) to 4He \( \to \Lambda N(2N) \) could give signatures in the missing mass spectra that had an exactly localizable counterpart in the \((\Lambda N)\) invariant mass ones, the central (and largest) part of the latter could not be explained as easily. The possible interpretation of it being due to an absorption in the \( \Sigma(3N) \) or \( \Lambda N(2N) \) final state followed by electromagnetic \( \Sigma^0 \to \Lambda \gamma \) decay or \( \Sigma N \) conversion, or to the decay of a possible strange di- or tri-baryon, was left open by them.

LNF-FINUDA [10] could study \( K^- \) absorption reactions on several heavier nuclei, from 6Li to 51V. Its experimental setup consisted of a large acceptance (> 2\( \pi \) sr) magnetic spectrometer with high momentum resolution and particle identification performance, able to deliver complete information on the event topology with a full reconstruction of all the charged particles participating to the \( K^- \) induced interaction. The presence of several different targets allowed the simultaneous measurement of the same final state produced by a \( K^- \) interacting on different nuclei. FINUDA could provide high resolution inclusive and exclusive momentum spectra for protons, \( \Lambda \)’s and charged light hadrons and showed clearly that the measurement of a single observable is by no means enough to draw any reliable conclusion on the possible existence of kaon-nuclear bound states. Only coincidence measurements and the analysis of several different distributions (momenta, invariant mass spectra, angular distributions) could provide a thorough description of the absorption process and help understanding its mechanism.

In this respect, FINUDA could finally disprove the initial claim for a tri-baryon waived by the KEK-E471 experiment [11] (lately withdrawn [12]), which was based on the presence of a bump observed in the inclusive proton and neutron momentum spectrum at about 500 MeV/c, for \( K^- \) absorption in 4He. FINUDA high statistics inclusive proton spectra do not show any monochromatic signal, except for 6Li, being it the clear signature of the quasi-free two-nucleon absorption \( K^- d \to \Sigma^- p \) occurring on the quasi-deuteron subcluster of 6Li [13].

More complete information than that obtained by inclusive spectra is carried by invariant mass distributions and angular correlation plots. The first FINUDA observations, which will be briefly described in the following, were actually based on these.

Complementary information can also be provided by the study of the missing mass distributions, as demonstrated by the E549 analyses [8, 14], which help identifying phase-space regions exclusively populated by defined reactions. Applying this method also to FINUDA data (considering for instance the lightest available target, 6Li), the results obtained are basically in agreement with E549 issues, concerning both \( \Lambda p \) and \( \Lambda d \) final states.

In the following, a summary of the experimental observations by FINUDA in the analysis of final states featuring \( \Lambda p \), \( \Lambda d \) and \( \Lambda t \) pairs will be given.

### STUDY OF \( K^- pp \) INTERACTION: \((\Lambda p)\) CHANNEL

According to the Akaishi-Yamazaki model [3], the simplest kaon-nucleon aggregate, beyond \( \Lambda(1405) \), should be \( (K^- pp) \). The presence of the \( K^- \) should attract two bound protons to form a state bound by 48 MeV, corresponding to a mass of 2232 MeV/c\(^2\), and with a width of 61 MeV, that could be observed after its non-mesonic decay in a \( \Lambda p \) pair.

An enhancement in the invariant mass spectrum of the \((\Lambda p)\) system was observed by FINUDA [15], for back-to-back \( (\Lambda p) \) pairs in events from light targets, 6Li, 7Li and 12C. The enhancement could not be explained by a simple \( K^- \) absorption on the \( \Lambda \) nucleus in the \( \Lambda p \) channel, leaving the \( \Lambda \)’s daughter nucleus in the ground state. Such a reaction would require a peak corresponding to its threshold, while the observed signal has a significantly lower mass.

This enhancement could be fitted by a Lorentzian curve and to its mass the value \((2255 \pm 9)\) MeV/c\(^2\) could be formally assigned, corresponding to a binding energy \( B_{K^-} = (115^{+15}_{-10}(stat) + 2^{+2}_{-2}(sys)) \) MeV, and a width \( \Gamma = (67^{+14}_{-11}(stat) + 5^{+5}_{-5}(sys)) \) MeV. Fig. 1 shows the observed enhancement in the \((\Lambda p)\) invariant mass spectrum without and with (inset) the acceptance correction. The back-to-back angular correlation of the observed \( \Lambda p \) pair emerged naturally from the data before applying any selection cut. Moreover, it was a constant feature of the data independent of the target where the \( K^- \) absorption occurred [16].

A possible simple interpretation of the signal was suggested by Magas et al. [7], and did not need a bound kaonic...
FIGURE 1. Invariant mass of the $(\Lambda p)$ system, for $K^-$ interactions in the $^6\text{Li}$, $^7\text{Li}$ and $^{12}\text{C}$ targets of FINUDA [15]. The events were selected with the $\Lambda$ and the proton almost back-to-back. In the inset the spectrum obtained after acceptance correction is shown, together with a fit with a gaussian convoluted Lorentzian function to extract the signal features. The fit was performed in the $(2.22 - 2.33)\text{ GeV}/c^2$ interval. The points out of this range are not included in the fit since affected by large errors due to the huge acceptance correction.

system to be formed: the bump could be simply due to the effect of angular cuts applied to a phase space distribution distorted by Final State Interactions (FSI). The interpretation seems sensible in that surely a sizeable effect from FSI’s should be present, especially since most of the events are due to $K^-^{12}\text{C}$ interaction, for which this effect should be more marked. However, in order to reproduce the line-shape of the $(\Lambda p)$ invariant mass distribution a very large contribution from FSI is required (some 90% for $^{12}\text{C}$), which seems to be overestimated.

The absorption into $\Sigma^0 p$ could indeed explain the observed back-to-back topology, as suggested also by the analysis of E549 [8]. However the relative branching fractions of the two channels $(\Lambda p/\Sigma^0 p \sim 4)$, as measured by the first absorption experiments [1], suggest that the strength of such a signal cannot be as large as to justify experimental observation.

More information on the role played by $\Sigma^0$ production in the kaon absorption can be gathered by means of the missing mass method, applied to data from a single nuclear species – $^6\text{Li}$ being the best choice for the relative simplicity of the nuclear structure, with a limited distortion due to FSI. This method exploits nicely the information from the $\Sigma^0$ decay, which fixes to 77 MeV the mass difference between the $\Lambda p$ and $\Sigma^0 p$ contributions, which can be thus separated quite clearly. From this analysis [17] it turns out that just a small fraction of the observed enhancement can due to the $\Sigma^0$ excitation and/or its conversion (as also shown by simulations). This result is basically in agreement with the E549 findings [8]. Using just $^6\text{Li}$ data, the invariant mass $(\Lambda p)$ spectrum as well as the back-to-back $\Lambda p$ angular distribution for the missing-mass selected events is in complete agreement with the first FINUDA result [15].

STUDY OF $K^- ppn$ INTERACTION: $(\Lambda d)$ CHANNEL

According to the model by Akaishi and Yamazaki, the tri-baryon kaonic states should be observed at a mass $(3120–3152)\text{ MeV}/c^2$, with a binding energy of $(170–190)$ MeV and a width of $(13–21)$ MeV, depending on the isospin configuration of the system.

Using the invariant mass method, a first exclusive analysis of the FINUDA data led to the observation of a strong $(\Lambda d)$ correlation compatible with the existence of a $(K^- ppn)$ system bound by about 60 MeV [18]. An amount of 25 events coming from $K^-$’s stopping in the two available $^6\text{Li}$ targets was collected in the first FINUDA data taking. The observed invariant mass spectrum of the $(\Lambda d)$ pair is shown in Fig. 2.

A more refined analysis of the $^6\text{Li}$ sample only, based also on a missing mass identification of the observed signals, has been done [17]. In the $(\Lambda d)$ invariant mass spectrum the contribution of the absorption reaction on three nucleons, $K^-^{0}\text{Li} \rightarrow \Lambda dt$, can be easily singled out, and at a larger mass value, before the opening of the $\Sigma^0$ threshold, other contributions can be seen. They hint to a possible superimposition of states in the mass region where the first published large bump was found. All the events in this region always feature the usual, marked back-to-back angular correlation.
FIGURE 2. Invariant mass of the $\Lambda d$ system for events from the $^6\text{Li}(K^-\text{stop},\Lambda d)3\text{N}$ reaction. The solid line is a fit of the experimental spectrum (histogram) by means of a Gaussian, used to reproduce the signal, and a linear combination of functions reproducing the $[\Lambda d\text{nnp}, \Lambda d\text{nd}]$ and $[\Lambda d\text{tK}^-3\text{N}]$ absorption reactions [18]. The $K^-\text{ppn}$ threshold is indicated in the figure by an arrow.

The contribution of the $\Sigma^0d$ channel in this region does not seem to be relevant, as in the $\Lambda p$ case.

A similar study was performed by the E549 experiment in the $^4\text{He}(K^-\text{stop}, d)$ reaction [9]. This experiment had a strong acceptance limitation, as it could only detect back-to-back $p-d$ pairs. The peak they observe at a larger ($\Lambda d$) invariant mass, after the acceptance correction, shifts downwards and becomes fully compatible with the FINUDA observation [9].

STUDY OF $K^-\text{ppnn}$ INTERACTION: ($\Lambda t$) CHANNEL

FINUDA can detect with good efficiency and negligible contaminations tritium nuclei (tritons) with a minimum momentum of 450 MeV/c. Coincidence events in which a triton was accompanied by a $\pi^-$ and a proton were found [19]. The invariant mass of the $(\pi^- p)$ pair clustered around the $\Lambda$ mass value, with practically no background, as shown in Fig. 3: a very clean $(\Lambda\pi^-)$ correlation was measured.

FIGURE 3. Invariant mass distribution of the $(\pi^- p)$ pairs detected in coincidence with a triton, from all FINUDA targets.

Both the triton and the $\Lambda$ had large momenta ($>450$ MeV/c), and a marked back-to-back angular correlation. $K^-$ induced interactions with the production of a $\Lambda$ and a triton in the final state had never been measured before, except from a pioneering bubble chamber experiment that reported the observation of three events only, which however
were also kinematically compatible with the \( Adn \) hypothesis [20]. FINUDA could detect a total of 40 events produced in several light targets, namely \(^6\text{Li} \), \(^7\text{Li} \) and \(^9\text{Be} \). The measured capture rate, averaged on all the involved nuclei, was around \( 10^{-3}/K^{-}\text{stop} \), a value in agreement with those typical of kaon absorptions.

The observed events were too few to draw any conclusion about the existence of a strange four-baryon. However, interesting hints emerged from phase space simulations of several possible \( K^- A \rightarrow \Lambda \Delta A'X \) reactions, indicating a most likely occurrence of a \( K^- \) absorption by many nucleons [19].

**CONCLUSIONS**

The new data collected recently by KEK-E549 and FINUDA help shedding light on the features of \( K^- \) absorption on nuclei. This topic was not studied very extensively in the past so the new data can start giving useful indications on the existence of aggregates formed by nucleons kept together rather strongly by a binding \( K^- \).

Interesting hints were found in the analysis of angular correlations of \( \Lambda p \), \( \Lambda d \) and \( \Lambda t \) pairs: the back-to-back emission of those particle could suggest to interpret them as the decay products of an intermediate strange multinucleon state. The presence of this correlation was found independently on the hit nucleus, which indicates the existence of a basic mechanism for their production different from a simple rescattering of the final state phase space particles.

Other information can be obtained by the analysis of the invariant and missing mass spectra, and from momenta distributions. The dependence on \( A \) of the observed shapes is an important benchmark to verify the effects of Final State Interactions. The data collected by FINUDA span the \((6 \div 51)\) atomic number range and amount to about \( 1 \text{ fb}^{-1} e^+ e^- \) integrated luminosity collected at the \( \phi (1020) \) peak at DAΦNE. Their analysis, for all targets, is currenty underway and many interesting new indications are expected to come in the next future to complete the present understanding of the \( K^- A \) dynamics.

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