Studies of $K^-$ absorption on light nuclei and the search for bound nuclear kaonic states

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Abstract. The available experimental data on $K^-$ absorption on nuclei are rather old and scarce: they are not enough to understand the possible formation of aggregates of nucleons bound together by a kaon, known as “Bound Kaonic Nuclear States”. The existence of such structures, suggested by a few theoretical models, has not been experimentally ascertained yet. To be observed, their width should be less than their binding energy. A possible decay channel for such states is the non mesonic one, leading to hyperon-nucleon (or light nuclei) final states. Therefore, experimental investigations of possible signatures are mainly based on the analysis of hyperon-nucleon(s) correlations (for instance, of $\Lambda p(d,t)$ pairs) and of invariant mass spectra. Complementary information may also be gathered from missing mass distributions. Recent experiments revived, with much larger statistics, the study of $K^-A$ absorption in light nuclei: namely, KEK-E549 studied the $K^-$ interactions on $^4$He, while FINUDA at DAΦNE collected a large statistics on $K^-\,^6,^7$Li, $K^-\,^9$Be and $K^-\,^{12}$C. The experimental results obtained so far by the various experiments studying the $K^-$ absorption in nuclei are here summarized.

1. $K^-$ absorption: general overview

Information on the $K^-\,\text{stop}$ absorption in nuclei can be obtained by studying the particles emitted following the $K^-$ interaction. A negative kaon, when interacting with a nuclear system, gets usually absorbed in the nuclear periphery. Information on nuclear densities and composition in the nuclear tail region, as well as on the Fermi motion of the outmost nucleons, must be used as input to understand the $K^-$ capture mechanism, and consequently the features of possible $K^-$-nuclei energy levels and shifts.

Until recently, the available data on $K^-$ absorption processes in a nucleus were scarce and rather old, dating back to bubble chamber experiments [1, 2]. The existing database was rather sparse: only in the last few years it has been fed by a good amount of new data, collected by experiments at KEK on $^4$He and at LNF on heavier nuclei.

$K^-$ absorption processes could possibly be mediated by 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 also the subject of future planned experiments. From the theoretical point of view a general consensus on their existence, or at least their observability, is however still missing [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, the \( K^- \) interaction can also 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 considered as an intermediate step following the few-nucleon absorption of a \( K^- \). Then, this system can undergo a non-mesonic decay in a pionless final state composed by a hyperon (typically a \( \Lambda \)) and nucleons or light nuclei (\textit{i.e.} deuterons and tritons). The non-mesonic decay is enhanced if the binding energy of such a strange cluster is larger than 110 MeV, which prevents the \( \Sigma \pi \) channel to be accessed.

The hyperon emitted in a multinucleon kaon absorption has a rather large momentum (\( > 500 \) MeV/c), which allows a clear separation of this reaction from the single-nucleon one. First bubble chamber experiments measured the production rates of hyperons in pionless final states only on \( ^4\text{He} \) [1], reporting around 12\% (per \( K^- \text{stop} \)) for the non-mesonic production of \( \Lambda \) (and \( \Sigma^0 \)), and respectively 1\% and 3.6\% for the non-mesonic production of \( \Sigma^+ \) and \( \Sigma^- \). 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. This trend confirms the peripheral feature of the absorption process [1].

Also the nucleons (light nuclei) emitted together with the hyperons in few-nucleon absorption processes are characterized by high momenta. Old bubble chamber experiments had not enough resolution to measure precisely high momentum particles. Therefore, their final results were given in the form of inclusive or semi-inclusive momentum spectra depleted in the high momentum region. To provide thorough information on absorption processes full spectrometers are needed. New generation experiments have been built able to provide full topologic and kinematic information, and new results have been obtained giving further insight on the \( K^- \) absorption process.

KEK-E549 collected a high statistics on the \( K^- \)-\( ^4\text{He} \) interaction [8, 9]. It was able to separate, by means of the missing mass method, the contribution of several reactions leading to the observed \((\Lambda N)\) final state. While the \( K^- \)-\( ^4\text{He} \) reaction, followed by \( \Sigma \) conversion, and the \( K^- \)-\( ^6\text{He} \) reaction \((\Lambda N(2N))\) one could give clear signatures in the \((\Lambda N)\) invariant mass spectrum, the central (and largest) part of this distribution could not be explained as easily. A possible interpretation of it can be the kaon absorption in the \((\Sigma^0 N(2N))\) final state followed by electromagnetic \( \Sigma^0 \rightarrow \Lambda \gamma \) decay or \( \Sigma N \) conversion, or the decay of a possible strange di- or tri-baryon. The possibility was left open by the Authors and the analysis is still presently ongoing [9].

LNF-FINUDA [10] is studying \( K^- \) absorption reactions on several nuclei heavier than \( ^4\text{He} \), from \(^6\text{Li}\) to \(^{51}\text{V}\). It is, at present –and probably will be for a long time in the future– the only experiment providing large statistics on \( K^- \text{stop} \) interaction on nuclei, at least up to \( A = 16 \). Its experimental setup consisted of a large acceptance (\( > 2\pi \text{ sr} \)) magnetic spectrometer with high momentum resolution and good particle identification performance, able to provide complete information on the event topology with a full reconstruction of all the charged particles emitted in the \( K^- \) induced interaction, together with neutrons which could be measured by means of its Time-Of-Flight equipment. The presence of several different targets allowed the simultaneous measurement of \( K^- \text{stop} \) interactions on different nuclei. FINUDA could provide high resolution inclusive and exclusive momentum spectra for protons, \( \Lambda \)’s and charged light hadrons. Coincidence measurements pointed out the poor reliability of single inclusive observables to draw any realistic conclusion on the possible existence of kaon-nuclear bound states. The measurement of many observables and the analysis of several different distributions (momenta, invariant and mass spectra, angular distributions) must be exploited to provide a thorough description of the absorption process and to understand its mechanism.

In this respect, FINUDA disproved the initial claim for a tri-baryon by the KEK-E471 experiment [11] (lately withdrawn [12]), which was based on the presence of a bump in the inclusive proton momentum spectrum at about 500 MeV/c, for \( K^- \) absorption in \(^8\text{He} \). FINUDA
high statistics inclusive proton spectra did not show any monochromatic signal, except for $^6\text{Li}$, being it the clear signature of the quasi-free two-nucleon absorption $K^- d \rightarrow \Sigma^- p$ occurring on the quasi-deuteron subcluster of $^6\text{Li}$ [13]. Fig. 1 shows the typical shape of the inclusive proton spectrum out of $^6\text{Li}$ (left) and of $^{12}\text{C}$ (right); in the second plot the contribution due to the $K^- d \rightarrow \Sigma^- p$ reaction is not observed.

![Figure 1. Inclusive proton spectra from FINUDA [13] following the $K^-$ capture at rest in $^6\text{Li}$ (a) and $^{12}\text{C}$ (b).](image)

Invariant mass distributions, together with the angular ones, provide of course more reliable information compared to inclusive spectra, which give indications on the missing energy only. The main FINUDA results, which will be described in the following, were actually based on invariant mass spectra, angular correlations and momentum and missing mass distributions.

However, as shown in the E549 analyses [8, 14] complementary information can also be provided by the missing mass distributions, which help identifying phase-space regions exclusively populated by defined reactions. This study can also be performed with the FINUDA data and the obtained results, as will be described later, are basically in agreement with E549 issues, concerning both $\Lambda p$ and $\Lambda d$ final states.

2. 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 unbound 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] in a first analysis, performed on a reduced data sample, selecting only events with back-to-back ($\Lambda p$) pairs from all the available light targets, namely from $^6\text{Li}$, $^7\text{Li}$ and $^{12}\text{C}$. The enhancement could not be explained by a simple $K^-$ absorption by the $\Lambda$ nucleus in the $\Lambda p$ channel, leaving the $\Lambda'$ daughter nucleus in the ground state. Such a reaction would require a peak corresponding to its threshold, while the observed signal had a significantly lower mass. The observed ($\pi^- p)p$ system featured an intrinsic back-to-back correlation even prior to selection criteria aiming to the $\Lambda$ identification.
The observed 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 \(B_{\Lambda K} = (115^{+6}_{-5}(\text{stat})^{+3}_{-2}(\text{sys}))\) MeV, and a width \(\Gamma = (67^{+12}_{-11}(\text{stat})^{+2}_{-3}(\text{sys}))\) MeV. Fig. 2 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, as already mentioned, emerged naturally from the data before applying any selection cut. Moreover, the angular correlation, as well as the enhancement in invariant mass, was a constant feature of the data independent of the target where the \(K^-\) absorption occurred [16].

![Figure 2](image)

**Figure 2.** Invariant mass of the \((\Lambda p)\) system, for \(K^-\) interactions in the \(^6\)Li, \(^7\)Li and \(^{12}\)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 \((2.22 - 2.33)\) 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.

A possible simple interpretation of the signal was suggested by Magas et al. [7], and did not require a bound kaonic system to be formed: the bump could be simply due to a reshaping effect of the applied angular cuts on the phase space distribution of the emitted particles, after their Final State Interactions (FSI). The interpretation seems sensible in that surely a sizeable effect from FSI’s should be present, especially for \(K^{-12}\)C interaction which plays the dominant contribution in the cumulated plot. However, in order to reproduce the line-shape of the \((\Lambda p)\) invariant mass distribution, in the calculation a very large contribution from FSI is required (some 90% for \(^{12}\)C), which seems to be an overestimation. Moreover the back-to-back correlation is an intrinsic feature of the available data, so the angular cuts hardly bias the distribution shapes as much as the model suggests.

An alternative explanation suggests the observed \((\Lambda p)\) pairs to be the final state products of a heavier kaonic cluster [6]. If this were the case, signatures of additional participating nucleons should be found.

The absorption leading to \(\Sigma^0 p\) final state 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 bubble chamber experiments [1], suggest that the strength of such a signal cannot be as large as to justify the experimental observation. An analysis of the missing mass spectrum, based on the expected missing photon signal (77 MeV missing energy) can help disentangling the contribution played by reactions with \(\Sigma^0\) production, as compared to those with a \(\Lambda\) hyperon.
In order to pin down the effective FSI contribution as well as those due to Quasi-Free absorption reactions, an analysis on a single type of nucleus (instead of the statistics cumulated on several different light targets, as in [15]) ought to be performed. Moreover, dealing with one type of nucleus in the initial state, the missing mass method can be fruitfully applied to get information on the role played by $\Sigma^0$ production in the kaon absorption, as well as by selected Quasi-Free reactions.

The statistics collected by FINUDA allows indeed to perform a complete analysis on $K^{-}\bar{p}\Lambda$ events [17] as well as on $K^{-}$ interactions on $^7$Li and $^9$Be, separately. Results on $^6$Li, the lightest target available in FINUDA, can be considered as reference as this nucleus is affected by a very limited FSI rescattering, and features a particular nuclear structure. $^6$Li, in fact, has a well known "quasi"-\( \alpha + " \) "quasi"-\( d \) cluster structure (feature already exploited in the analysis of inclusive proton spectra mentioned above). The results obtained on $^6$Li basically confirm the first issues [15], while adding many more interesting insights to the subject. With the available FINUDA data a thorough study of missing mass, invariant mass, inclusive momentum spectra and angular correlations can be performed.

The enhancement in the (\( \Lambda p \)) invariant mass spectrum persists also in the case of $^6$Li data. The missing mass analysis shows that just a small fraction of the observed enhancement can be due to the $\Sigma^0$ excitation and/or its conversion, in basic agreement with the E549 findings [8]. In fact, in the missing mass spectrum of the $^6$Li($K_{\text{stop}}^{-}, \Lambda p$)$X$ reaction the contribution of the quasi-free two nucleon absorption $K_{\text{stop}}^{-}\bar{p}^6\text{Li} \rightarrow \Lambda p^4\text{He}_{\text{g.s.}}$ can be observed, as a peak centered around 3760 MeV/$c^2$. The contribution of the $K_{\text{stop}}^{-}\bar{p}^6\text{Li} \rightarrow \Sigma^0 p^4\text{He}_{\text{g.s.}}$ reaction opens 77 MeV/$c^2$ beyond. At about 3870 MeV/$c^2$ the mesonic channel opens, $K_{\text{stop}}^{-}\bar{p}^6\text{Li} \rightarrow \Lambda p\Sigma^0 p^4\text{He}_{\text{g.s.}}$, and a sharp spike at threshold appears which is likely to be due to a cusp effect. This spike has a counterpart in the (\( \Lambda p \)) invariant mass spectrum as a rather narrow peak (20-30 MeV/$c^2$ wide) at about 2220 MeV/$c^2$. The appearance of a sharp enhancement at threshold is a well known effect already observed in the early bubble chamber experiments [18]. Several observations for such signals have been reported in the years, especially on deuterium. Moreover, in the same mass region a narrow signal was also observed by the OBELIX experiment in the annihilation reaction on $^4$He: $\bar{p}^4\text{He} \rightarrow (pn^-)pK^0_X$ [19].

All the events selected in different missing mass ranges for the mentioned reactions feature the same marked back-to-back trend in the $\cos \Theta_{\Lambda p}$ angular distribution.

As in E549 [9], the identified contributions are however not enough to describe thoroughly the invariant mass spectrum. The central part of the distribution, beyond the quasi-free $\Lambda p$ production but below the $\Sigma^0 p$ one, cannot be reproduced by the mentioned mechanisms. Dedicated simulations show that this region, which corresponds, in the invariant mass plot, to the (2230 – 2330) MeV/$c^2$ range, cannot be satisfactorily reproduced by a quasi-free production of a $\Sigma^{0,\pm}$ followed by its nuclear conversion into $\Lambda N$. In fact, in this case neither one would get back-to-back angular distributions, nor the contribution of these reactions to the invariant mass (\( \Lambda p \)) spectrum is located in the region of interest.

3. 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) 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.

A first study of the invariant mass spectrum of back-to-back correlated (\( \Lambda d \)) pairs led to the observation of an enhancement at 3251 MeV/$c^2$ (35 MeV wide), that could be related to the existence of a ($K^-ppn$) system bound by about 60 MeV [20]. A first analysis was based on an overall amount of 25 events only. The observed invariant mass spectrum of the (\( \Lambda d \)) pair is shown in Fig. 3.
Figure 3. Invariant mass of the ($\Delta d$) system for events from the $^6$Li($K^-_{stop}$, $\Delta d$)3N 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 $[\Delta d]np$, $[\Delta d]nd$ and $[\Delta d]t K^-(3N)$ absorption reactions [20]. The $K^-ppn$ threshold is indicated in the figure by an arrow.

Using the full available statistics on $^6$Li target ($\sim 8 \times$ the first sample) a more refined analysis of $K^-6$Li was possible, based, as well as in the $\Delta p$ case, on a missing mass identification of the observed signals [17]. In the $^6$Li($K^-_{stop}$, $\Delta d$)X missing mass spectrum the contribution of the absorption reaction on three nucleons, $K^-6$Li $\rightarrow \Delta dt$, can be easily spotted as a peak at the triton mass. This signature indicates that the interpretation of Magas et al. [21], stating that the first observed ($\Delta d$) invariant mass spectrum, as well as the ($\Delta d$) angular correlations, can be plainly explained by three-nucleon absorption, may be used to reproduce a part of the experimental data.

On the other hand, the interpretation of the observed structure being due to the absorption on a “quasi”-$\alpha$ could be strengthened by measuring a coincidence neutron carrying away the $\sim 25$ MeV excess kinetic energy. The analysis of neutron coincidences is currently underway.

At larger missing mass values, before the opening of the $K^-6$Li $\rightarrow \Sigma^0dt$ channel (again, clearly visible as an enhancement in the spectrum), other narrow contributions can be seen. They hint to a possible superimposition of states in the mass region where initially, with very few events, a large bump was found. All the events in this region always feature the peculiar, marked back-to-back angular correlation. The contribution of the $\Sigma^0d$ channel in the measured spectrum is not as relevant as in the $\Delta p$ case.

A similar study was performed by the E549 experiment in the $^4$He($K^-_{stop}$, $d$) 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 ($\Delta d$) invariant mass, after the acceptance correction, shifts downwards and becomes fully compatible with the FINUDA observation [9].

4. Study of $K^-ppnn$ 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 [22]. The invariant mass of the ($\pi^-p$) pair clustered around the $\Lambda$ mass value, with practically no background. As shown in Fig. 4 a very clean ($\Lambda$-$t$) correlation was measured.

Both the triton and the $\Lambda$ had large momenta (> 450 MeV/c), and again a marked back-to-
Invariant Mass (MeV/c$^2$)

Counts / 5 MeV/c$^2$

1050 1100 1150 1200 1250 1300 1350

Figure 4. Invariant mass distribution of the $(\pi^- p)$ pairs detected in coincidence with a triton, from all FINUDA targets.

$K^-$ 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 $\Lambda dn$ hypothesis [23]. 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.

Figure 5. Diffusion plot of the momenta of the triton and the $\Lambda$ for experimental events by FINUDA (stars) superimposed to the results of phase space simulations, filtered though the apparatus acceptance, of the reactions: a) $K^-_{\text{stop}} A \rightarrow \Lambda t A'$ (scatter plot) and $K^-_{\text{stop}} A \rightarrow \Sigma t A'$ (contour plots), and b) $K^-_{\text{stop}} A \rightarrow \Lambda t N A'$.

The observed events were too few to draw any conclusion about the existence of a strange four-baryon. However, interesting hints emerged comparing the experimental distributions with phase space simulations of several possible $K^- A \rightarrow \Lambda t A' X$ reactions. Fig. 5 shows the momenta scatter plot for the triton and the reconstructed $\Lambda$ (stars) superimposed to the result of a phase space simulation (filtered through FINUDA acceptance) of a) $K^-_{\text{stop}} A \rightarrow \Lambda t A'$ ($K^-_{\text{stop}} A \rightarrow \Sigma t A'$
as contour plots) and b) $K_{\text{stop}}^- A \rightarrow AtNA'$. The occurrence of a $K^-$ absorption by four nucleons, in a pionless final state featuring a triton and a $\Lambda(\Sigma^0)$ or a $\Lambda N$ pair, seems to be likely [22].

5. 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 eventually give 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 $A_p$, $Ad$ and $At$ pairs: they all feature a back-to-back trend. In the case of $A_p$, the presence of this correlation was found to be independent of the hit nucleus, which indicates the existence of a basic mechanism for their production different from a simple rescattering of the final state particles, which should be more sizeable the larger the mass number of the hit nucleus.

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 ($6 \div 51$) mass number range and amount to a ($e^+e^-$) integrated luminosity, collected at the $\phi(1020)$ peak at DAΦNE, of about 1 fb$^{-1}$. Their analysis, for a nucleus type at a time, is currently 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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