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Study of pionless two-nucleon K^- absorptions at rest with FINUDA

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An overview of the results achieved so far by the FINUDA experiment in the study of K^- absorption at rest by few nucleons in final states with a hyperon (Λ, Σ^-) and a proton is presented.

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1. Introduction

The processes of K^- absorption by two or few nucleons are of relevance since they are at the basis of the search for kaon-nuclear bound states, which are defined as aggregates of nucleons kept together by a negative kaon. The existence of such states was predicted several years ago [1] and recently a few experiments have been pursuing their search, but conclusive observations are still awaited. According to some theoretical models [2], even in the case of their existence, their widths would be so broad as to prevent their experimental observations. From the experimental point of view the search is based on the studies of reactions in which kaons are absorbed, preferably by light nuclei (to get cleaner experimental signatures), and produce hyperons and nucleons or light nuclei (such as deuterons and tritons) in the final state. These particles are expected to stem also from the non-mesonic decay of bound kaon-nucleon aggregates, with a peculiar angular correlation.

If the existing measurements of one-nucleon kaon absorption reactions are few [3], results on many-nucleon absorptions are even scarcer. Apart from a milestone work by Katz *et al.* [4], describing in good detail the interaction of K^-'s at rest on ^{4}He in a bubble chamber experiment, few more data, with large or even no quoted error, exist; they are restricted to the interaction of K^-'s on hydrocarbon mixture or Neon filled bubble chambers [5] or on nuclear emulsions, composed by mixtures of rather heavy nuclei [6]. In general, a superficial behaviour of the kaonic absorption can be inferred, but of course a dependence on the nuclear structure can exist and is worth being investigated. Precise measurements of kaon induced absorption rates are also needed as these reactions constitute the largest part of the background underlying the signals of hypernuclear states. The contribution of mesonless kaonic absorption reactions is as sizeable as 20% (in medium-heavy nuclei), and such a frequency calls indeed for more detailed studies of these processes.

The experimental signature of pionless multi-nucleon kaon absorptions is rather clean: hyperons and nucleons (or light nuclei) in the final state feature both a large momentum (say, larger than at least 400 MeV/*c*). For this reason their observation, with enough resolution, was not easily performed in old bubble chamber experiments. Modern magnetic spectrometers, on the other hand, can exploit their P.Id. capabilities and resolution to perform precise measurements of the particles produced in these reactions. One of them, thoroghly dedicated to the study of kaon induced interactions, was FINUDA, installed at the DAΦNE machine in LNF (Italy) [8].

In FINUDA negative kaons, coming from the $\phi(1020)$ decay, could be stopped in a set of eight targets, made of materials with a mass number chosen in the range $6 \leq A \leq 51$. In two data takings a total amount of about 1 fb^{-1} (e^+e^-) collisions were collected. The apparatus was a magnetic spectrometer with cylindrical symmetry able to track charged particles with a momentum resolution up to 0.6% FWHM, and a particle identification efficiency as large as 96% for pions and protons. It was completed by a time-of-flight system allowing the detection of neutrons with an efficiency of about 8% [3].

In the wealthiest of the two FINUDA data takings mainly p-shell nuclei were used as targets (solid: ^{6}Li, ^{7}Li, ^{9}Be; powder: ^{13}C; liquid: ^{16}O, in form of deuterated water). As long as the mass number of the hit nucleus increases, Final State Interaction (FSI) effects become sizeable and, as suggested by some Authors [7], the rescattering mechanism can severely spoil a clean observation of the final state particles' kinematics. For this reason, after a first exploratory study performed cumulating observations from a set of light targets [9], the efforts were focussed on the investigation of kaon absorptions in ^{6}Li, the lightest target nucleus used in FINUDA.

The ^{6}Li nucleus features a di-cluster structure, as measured in pionic absorption experiments [10], being formed by a rather loosely bound quasi-deuteron and quasi-α pair. Thus, studies of kaon absorption by ^{6}Li subclusters, in particular the quasi-deuteron, can be performed. The Fermi momentum of the ^{6}Li subclusters can be fairly modeled [11], so precise studies of quasi-free absorptions are possible. In addition, with a nucleus as light as ^{6}Li the effects of FSI's are reduced, and a cleanest experimental environment can be probed.

In this paper, an overview of the results achieved by FINUDA in the studies of semi-inclusive final states produced by the $K^- \, ^6$Li interaction and composed by a hyperon (Λ, Σ^-) and a proton is given. In the first case, hints on the $K^-(pp)$ absorption process can be gathered; in the second case, the $K^-(pn)$ absorption mechanism can be directly studied.

2. Study of the $^6\mathrm{Li}(K^-_{stop}, \Lambda p)X$ semi-exclusive reaction

Only a short summary is given here, as the most recent results have already been described in larger detail elsewhere [12]. In 2005 a top-cited paper by FINUDA [9] pointed out the existence of a bump structure, visible in the (Λp) invariant mass spectrum at about 2255 MeV, 67 MeV wide, that could not be explained by due to the simple Quasi-Free (QF) two-nucleon absorption reaction $K^- pp \to \Lambda p$. The events were characterized by a marked back-to-back correlation between the emitted Λ and p, which suggested as possible interpretation the existence of a $[K^- pp]$ state, 115 MeV bound, decaying in Λp. The analysis, performed over a sample of mixed light targets (^{6}Li, ^{7}Li and, mainly, ^{12}C), has been recently repeated just using ^{6}Li data. The features of the (Λp) invariant mass spectrum keep basically unaltered, as well as the angular correlation of the produced particles. A missing mass analysis has been performed, which helps disentangling the contributions of some QF two-nucleon induced reactions to the experimental sample. From this analysis, it appears that the $K^- pp \to \Sigma^0 p$ reaction, followed by the $\Sigma^0 \to \Lambda\gamma$ decay, is not enough to explain completely the experimental spectra. The possible contribution of $\Sigma\Lambda$ conversion reactions is currently being evaluated, but some of them can be ruled out by Monte Carlo studies, which indicate that their signatures are not compatible with all the experimental observations.

3. Study of the $^6\mathrm{Li}(K^-_{stop}, \Sigma^- p)X'$ semi-exclusive reaction

The starting point for the study of the $\Sigma^- p$ final state is the selection of a clean $np\pi^-$ sample. Details on the neutron detection and selection criteria can be found in [3]. Without kinematic cuts, but only the selection of high quality charged tracks, the signal from the Σ^- baryon, observed in its $\Sigma^- \to n\pi^-$ decay mode (B.R. = 99.85%), emerges with $S/B \simeq 1$. The background has therefore to be reduced trying to reject at best contributions from the reactions which feed the $np\pi^-$ final state. The main contamination is played by the QF two-nucleon absorption $K^-(pn) \to \Lambda n$, which can be discarded applying a cut on the invariant mass of the detected $(\pi^- p)$ pair and their angular correlation – the Λ is emitted with high momentum therefore the particles from its decay are mostly formard emitted. A second contamination comes from the QF one-nucleon induced $K^- p \to \Sigma^+\pi^-$ reaction, followed by a $\Sigma^+ n \to \Lambda p$ conversion and the $\Lambda \to n\pi^0$ decay. In this case, a π^0 is missing. The $\Sigma^-\pi^+$ QF one nucleon absorption occurs with a sizeable emission rate, of about 18%/K^-_{stop} in

^{6}Li [3], so the contamination of this channel could be quite important. These events can be rejected applying a cut on the secondary vertex distance and (eventually) on the missing mass of the full reaction. The most dangerous contamination comes from misidentifications of γ's by neutrons (and vice versa). For instance this can occur in the case of a single nucleon absorption into $\Sigma^+\pi^-$, with the following $\Sigma^+ \to p\pi^0$ decay (B.R. = 51.57%), and the fake assignment to a neutron of one of the γ's from the π^0 decay. These events have clearly unphysical kinematics and can be cut applying a selection in the missing mass distribution of the $^6\mathrm{Li}(K^-_{stop}, n\pi^- p)X'$ reaction, at 3σ from the minimum expected value for the mass of the X' system (namely, the mass of ^{4}He). This cut helps also in the rejection of neutrons undergoing a scattering before being detected.

From this sample, semi-inclusive $\Sigma^- p$ events can be selected by applying a cut on a narrow window (28 MeV) across the nominal Σ^- mass value. A further selection can be made taking into account that the products from its decay tend to have an angular correlation. This is shown in the scatter plot of Fig. 1, where the invariant mass of the $n\pi^-$ pair is plotted against the angle between the two particles: the distribution is depleted at forward angles ($\cos(n\pi^-) > 0.5$).

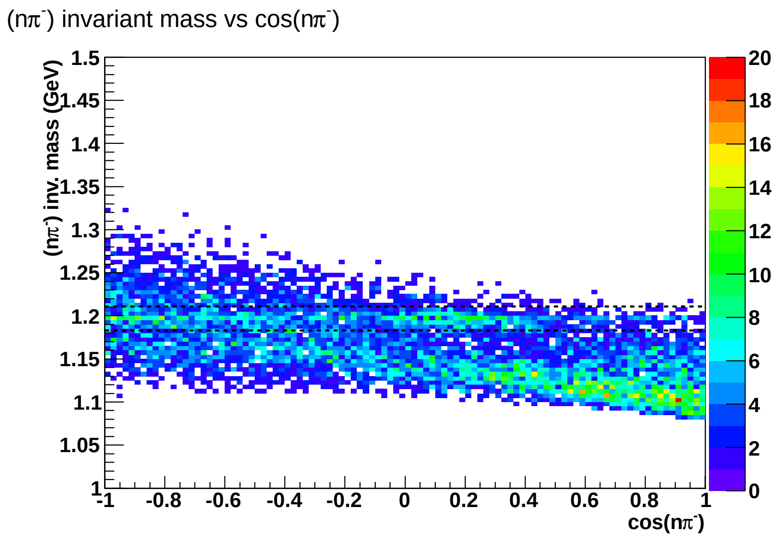

Figure 1: Scatter plot of the $(n\pi^-)$ invariant mass versus the angle between the two particles. The dashed lines mark the region across the nominal Σ^- mass value selected for the analysis. ^{6}Li data.

With the selected $\Sigma^- p$ events semi-inclusive sample missing mass studies can be performed to single out the contribution of exclusive QF two-nucleon kaon absorptions. The missing mass plot of the selected events is shown in Fig. 2a), while the invariant mass distribution of the $(np\pi^-)$ events is displayed in Fig. 2b). Centered at the ^{4}He mass (3.73 GeV), a peak appears in the missing mass distribution (blue area in the picture): these events belong to the exclusive $K^- \, ^6\mathrm{Li} \to \Sigma^- p \, ^4\mathrm{He}$ reaction. In the invariant mass distribution they are located at the higher mass side of the available phase space. Fig. 2c), which reports the angular distribution between the proton and the $(n\pi^-)$ pair selected in the Σ^- mass region, shows that for these particles a marked back-to-back correlation exists.

The hatched gray area in Fig. 2a) is populated, on the other hand, by events in which an additional pion is missing. These events fill the low mass region in the invariant mass plot, and they are distributed flatly over the angular correlation spectrum.

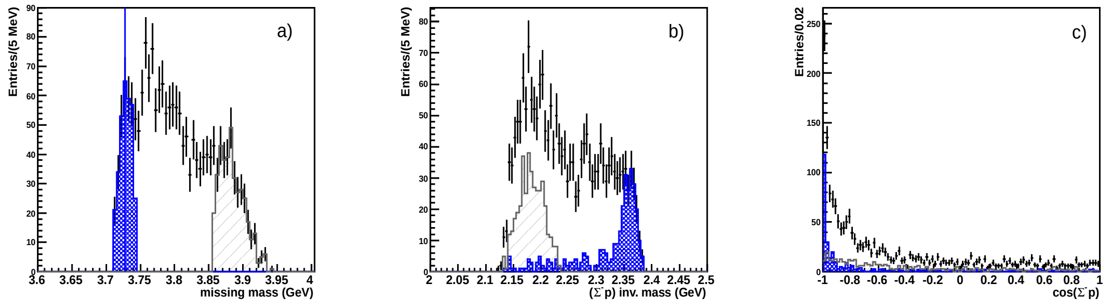

Figure 2: $\Sigma^- p$ semi-inclusive sample: a) missing mass spectrum of the $^6\text{Li}(K^-_{stop},\Sigma^- p)X'$ reaction; b) invariant mass spectrum of the $(\Sigma^- p)$ system; c) angular distribution of the angle between Σ^- and p. The plots are not acceptance corrected.

A sizeable part of the missing mass and invariant mass spectra cannot be explained just resorting to the two mentioned QF two-nucleon absorptions. Studies of the reactions filling the experimental spectra are currently underway. Possible contributions could be played by proton, pion and Σ^- rescattering reactions. However, their features hardly match those of all the available experimental distributions.

Fig. 3 shows the corresponding measured momenta for protons (a), pions (b) and neutrons (c). The blue distributions for pions and neutrons are monotonically rising, as expected for the decay daughters of a Σ^- of about 500 MeV$/c$. At this value, the proton momentum spectrum shows a peak, which indicates that the selected protons are actually the prompt particles in the $\Sigma^- p$ exclusive reaction.

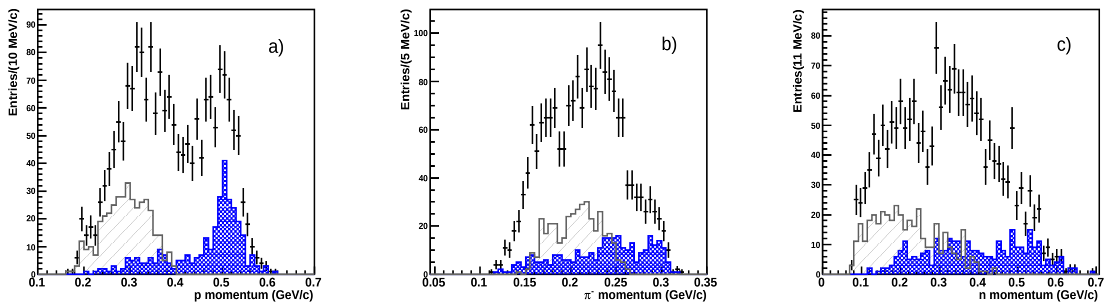

Figure 3: Momenta distributions for protons (a), π^-'s (b) and neutrons (c) selected in the $^6\text{Li}(K^-_{stop},\Sigma^- p)X'$ semi-inclusive sample. As in the previous Figure, the blue area is filled by events from the $\Sigma^- p$ exclusive reactions, the gray hatched one by events compatible with a missing pion. The plots are not acceptance corrected.

3.1 Emission rates of $K^- {}^A\text{Z} \rightarrow \Sigma^- p^{(A-2)}\text{Z}'$ exclusive reactions

Selecting the exclusive component of the missing mass plot it is possible to evaluate, for some p-shell nuclei, the emission rate of the $K^- {}^A Z \rightarrow \Sigma^- p^{(A-2)} Z'$ reactions. As expected, the selected

PoS(STORI11)049

events are characterized by high momentum hyperons and protons, as shown in the scatter plot in Fig. 4 which displays a clustering at about 500 MeV/c.

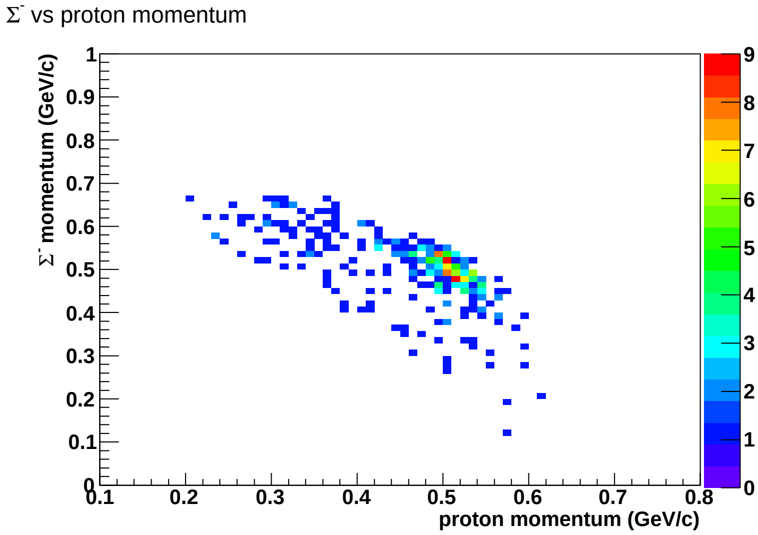

Figure 4: Scatter plot of the Σ^- versus proton momentum for events selected to belong to the $K^- {}^6\mathrm{Li} \rightarrow \Sigma^- p {}^4\mathrm{He}$ reaction. ^{6}Li data.

For the selected events the S/B ratio under the Σ^- peak is larger than 3, so reliable rate measurements can be performed. Fig. 5 shows the $(\pi^- n)$ invariant mass distributions for exclusive events (like those selected in the blue area of Fig. 2), for all the studied p-shell nuclei.

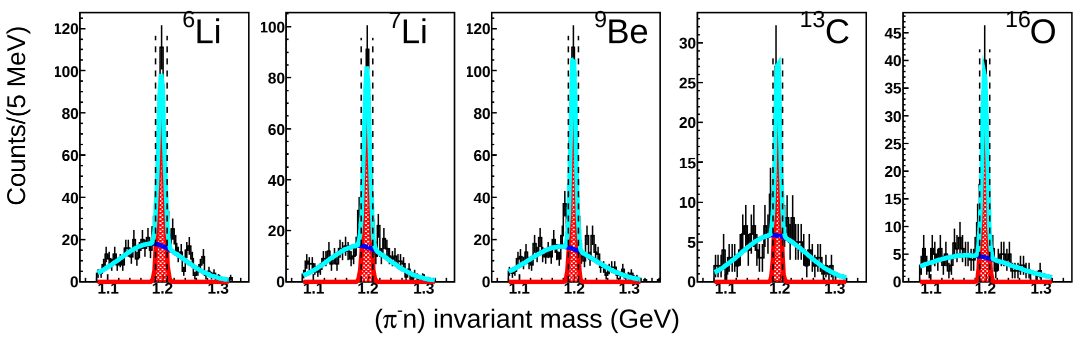

Figure 5: $(\pi^- n)$ invariant mass distributions for several p-shell nuclei studied by FINUDA. The light blue curve represents a total fit of the spectrum, obtained by the sum of a gaussian signal (red histogram) and a polynomial background (blue curve in the mass region of interest). The vertical dashed lines mark the region of interest, a $\pm 2\sigma$ interval centered at the Σ^- mass value obtained from the fit.

The $\Sigma^- p$ exclusive events were counted from the integral of the Σ^- peak in Fig. 5, to which a polynomial background (blue curve) was subtracted, in a $\pm 2\sigma$ range (marked by the dashed vertical lines).

The evaluated rate, per K^-_{stop}, measures the emission yield of $\Sigma^- p$, which does not take into account neither a possible subsequent π^- absorption nor the $\Sigma\Lambda$ conversion rates. Conversely, it takes into account the amount of Σ^-'s lost due to conversions at rest, as evaluated in [3].

The new measurements by FINUDA are reported in Fig. 6 (full blue dots) together with the few existing measurements, on ^{4}He [4] (red markers) and on ^{6}Li, performed by FINUDA in a first semi-inclusive analysis in which neutrons were not detected [13] (full blue square). New and old measurements are in good agreement.

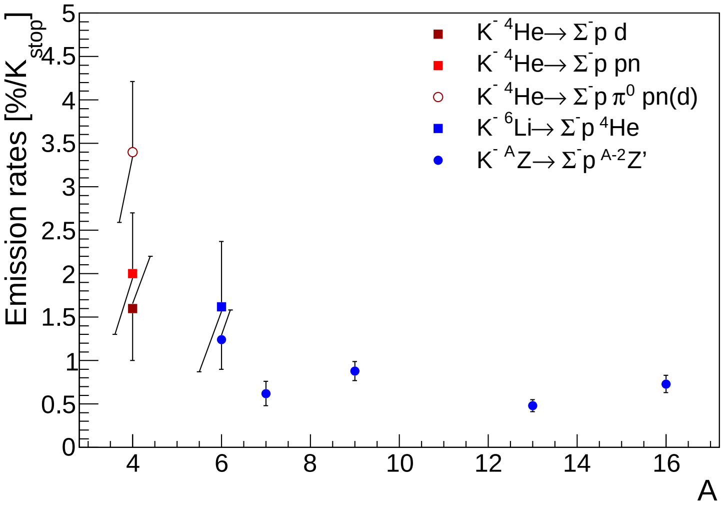

Figure 6: Emission rates of the $K^- \, ^AZ \to \Sigma^- p^{(A-2)}Z'$ exclusive reactions for several nuclei. Measurements on ^{4}He are from Ref. [4], measurements for $A \geq 6$ are by FINUDA.

4. Summary

The amount of data collected by FINUDA on ^{6}Li targets allowed to perform a parallel analysis on the Λp and $\Sigma^- p$ final states, to study different aspects of the kaon absorption by a nucleon pair, namely $[K^- pp]$ and $[K^- pn]$. In both cases a sizeable part of the experimental spectra fail to be explained by simple QF two-nucleon absorption reactions. As well, in both cases events are characterized by a marked back-to-back correlation of the hyperon-proton pairs. For the first time, an assessment of the emission rates of the exclusive $K^- \, ^AZ \to \Sigma^- p^{(A-2)}Z'$ reaction on some p-shell nuclei, with mass number in the range $6 \leq A \leq 16$ has been performed, completing a quite meager existing data set.

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