EPJ Web of Conferences **3**, 07003 (2010)
DOI:10.1051/epjconf/20100307003

Search for a bound K^-pp system

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Abstract. Data from the K^- absorption reaction on ^{6,7}Li, ^{9}Be, ^{13}C and ^{16}O have recently been collected by FINUDA at the DAΦNE ϕ-factory (Laboratori Nazionali di Frascati-INFN), following an earlier lower statistics run on ^{12}C and some other targets. FINUDA is a high acceptance magnetic spectrometer which performed a wide range of studies by detecting the charged particles and neutrons exiting the targets after the absorption event. In this paper it is discussed about the study of the A($K^-, \Lambda p$) reaction in the context of the search for deeply bound $\overline{K}$- nuclear states. The observation of a bump in the Λp invariant mass distribution is discussed in terms of a possible signature of a deeply bound K^-pp kaonic cluster as well as of more conventional physics. An overview of the experimental situation in this field will be given.

1 Introduction

The topic of $\overline{K}$ in nuclei has attracted a considerable interest in recent years, stimulated by a paper of Akaishi and Yamazaki predicting the existence of deeply bound kaonic nuclei (DBKN) with small width [1]. The I=0 $\overline{K}$ N potential is considered to be strongly attractive, so the formation of $\overline{K}$-nucleus bound states should in principle be possible; however, the strong absorptive part of the $\overline{K}$-nucleus potential should prevent the formation of narrow, experimentally detectable states.

The first predictions of a $\overline{K}$-nucleus bound state dates back to 1963 when Nogami [2] discussed the possible existence of a $\overline{K}$NN bound state. In 1986 Wycech suggested a possible mechanism which narrows the decay width [3]: if the antikaon-nucleus interaction is strongly attractive, the binding energy may be large enough (∼100 MeV) as to energetically close the main decay channel ($KN \to \Sigma\pi$) and narrow the width down to ∼20 MeV.

The possibility to form and detect narrow deeply bound kaonic nuclei obviously depends on the properties of the $\overline{K}$-nucleus interaction. There is however no consensus on its strength, and both moderate and strong potentials are described in the literature. Fits of the shifts and widths of kaonic atom levels suggest the possibility of a $\overline{K}$-nucleus interaction which is very strong (up to 200 MeV) and absorptive [4], while chirally based theories provide much shallower potentials (40-60 MeV) [5].

Akaishi and Yamazaki constructed their model starting from a phenomenological $\overline{K}$N potential which reproduces the mass and width of the $\Lambda(1405)$ predicting long lived, deeply bound, high density, light exotic states. A very lively and still open discussion started about the possibility of forming such states, but more recently the attention focussed on the simplest and lightest system, the K^-pp [6–9].

Despite the strong effort and the relevant number of theoretical studies recently performed there is still a rather strong discrepancy between different predictions. This is probably related to a great extent to the fact that the behaviour of the $\overline{K}$ N interaction below threshold, which is the relevant energy region for the DBKN, is extrapolated using the experimental $\overline{K}$-N scattering (and kaonic hydrogen) data above threshold. This subthreshold extrapolation is performed down to the ($\Sigma\pi$) threshold in a region where no experimental constraints are available and where the $\Lambda(1405)$, whose nature is still debated, plays an important role. The scenario of theoretical predictions appears therefore very scattered both with regard to the binding energies and the widths. While Akaishi and Yamazaki predicted a binding energy B.E.=48 MeV and a width Γ=61 MeV for the K^-pp system , other authors predict binding energies that vary from B.E.∼20 MeV (Γ=40-70 MeV) [6,7] to B.E.∼ 55-70 MeV ($\Gamma \sim 100 MeV$) [8] to B.E.∼120MeV (Γ=60 MeV) [9].

It appears therefore clear that the situation is far from being settled and that there is presently no common perspective on the subject of kaonic nuclear clusters. This is also related to the fact that there is a lack of experimental data that only very recently started to be filled. The present experimental situation will be described in the following section.

2 The experimental search for deeply bound kaonic clusters

To form a K^-NN cluster, the incoming K^- must interact with 2 or more nucleons inside a nucleus. The formation of such a state can therefore be viewed as an intermediate

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state of a 2-body absorption reaction, decaying into a YN final state (where Y is a Λ or Σ hyperon). A detailed study of the K^- multinucleon quasi-free absorption is therefore a crucial ingredient to highlight the possible formation of kaonic nuclear clusters since they will contribute to a relevant part of the background. A comprehensive study of $\bar{K}A$ clustering requires a full study of its possible decay products, that is momentum vector of hyperons and nucleons (or light nuclei, *i.e.* deuterons, tritons etc.) that are emitted in the decay. This allows for the determination of the kinematical observables which are necessary to establish the existence of DBKN states.

The experimental activity has recently witnessed an increase in the searches for DBKN by exploiting different techniques and formation reactions. Still, experimental results on K^- absorption on 2 or more nucleons are rather scarce in literature, with a relevant part of the experimental data produced by old bubble chamber experiments [10–12] which didn't have a good enough resolution to study high momentum (≥ 400-500MeV/c) protons and Λ's.

The first claims of DBKN's were related to inclusive measurements made by the E471 experiment at KEK-PS with a neutron or proton detected after K^- absorption at rest on liquid ^{4}He. The neutron and proton spectra, once reinterpreted as missing mass spectra, were used to claim the existence of two very deep and narrow strange tri-baryon states [13]. In particular, the tri-baryon state deduced from the $^4He(K^-_{stop}, p)$ spectrum, was assigned a binding energy B.E.=195 MeV and width $\Gamma \leq 25$ MeV which were in good accordance with Akaishi and Yamazaki predictions. Such conclusion was later called into question by a measurement performed by the FINUDA experiment which observed the inclusive spectra of protons emitted from ^{6}Li targets, ^{6}Li(K^-, p) [14]. Proton momentum spectra from ^{6}Li show a sizable signal at about 500 MeV/c [14] (see fig.1a)) which was interpreted as a proton emission after $K^-d \to \Sigma^-p$ two-body absorption on a "quasi-deuteron" subcluster of ^{6}Li. Such interpretation was made possible by the capability of FINUDA of detecting also $A(K^-, \pi^-p)$ coincidence events and determining particle emission vertices as well as πp kinematical correlations. Inclusive proton spectra on ^{12}C [14] (see fig. 1b)) and other A>6 targets (up to A=61) presently under analysis show a much smoother behavior, incompatible with the hypothesis of the presence of narrow kaonic nuclear states. This behavior was later confirmed also by a higher statistics and experimentally improved repetition of the E571 measurement of proton inclusive spectra after K^- absorption in ^{4}He [15] where the relatively narrow peak seen in [13] leaves place to a much wider bump. Even before FINUDA's results were available, theoretical interpretations [16] were made of the E571 proton bump as being due to two-body absorption reactions leading to the emission of almost monochromatic nucleon-hyperon pairs.

In the case of K^- absorbed at rest on two or more nucleons without pion emission the hyperon momentum is rather high (larger than 400-500 MeV/c). Experiments able to detect hyperons can therefore perform a clean separation between mesonic (single nucleon) and multinucleon absorption processes, the hyperon from the single nucleon absorption being confined below 400 MeV/c. FINUDA, described in the following section, is such an experiment, able e.g. to efficiently detect Λ's from 200 MeV/c up to 800 MeV/c. Still, no interesting signal could be found in the inclusive Λ spectrum.

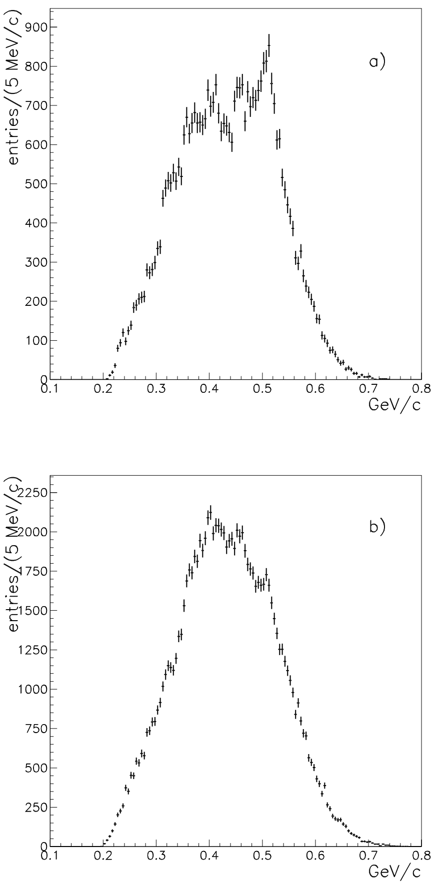

Fig. 1. Inclusive momentum spectra of protons [14] following the K^- capture at rest on ^{6}Li (a) and on ^{12}C (b). Data are from the FINUDA experiment.

The above results point to the fact that inclusive measurements, even on light systems, are inadequate to draw firm conclusions on the existence of DBKN since background contributions can be very sizeable and bring to wrong interpretations, especially if in absence of high statistics. Exclusive measurements are more appropriate to disentangle the possible signal from the background and in general to better understand the dynamics of the K^-A absorption reactions.

The method followed by the FINUDA experiment and described below, is that of measuring the vector momenta of final state particles so as to be able to measure the binding energy and width of the DBKN's from the invariant mass distribution of their decay products.

Also the E549-KEK experiment [17, 18] studied the Λp and Λn pairs from the ^{4}He$(K^-_{stop}, \Lambda N)X$ reaction. The low mass of the system and an analysis in terms of invariant and missing mass variables allow to get a deeper under-

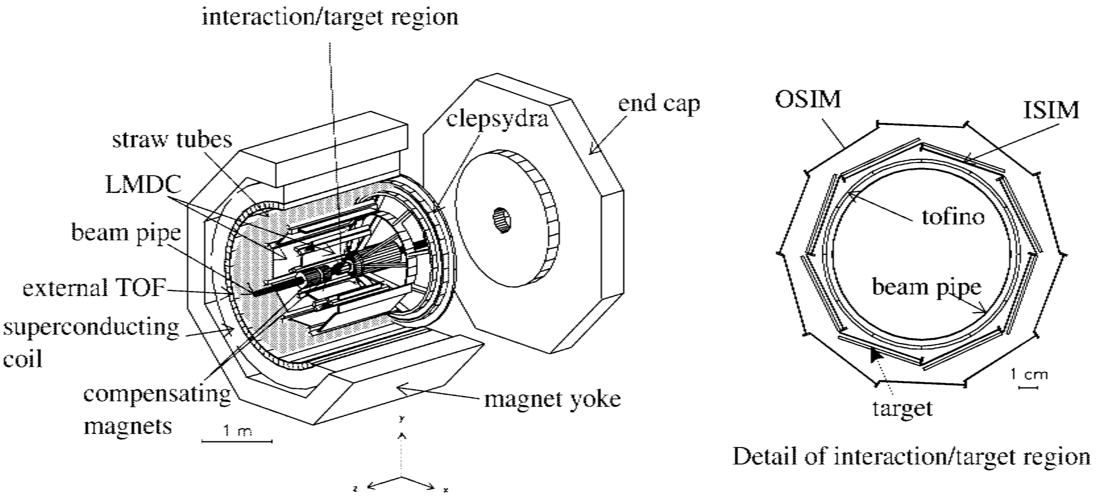

Fig. 2. Left: sketch of the FINUDA spectrometer. Right: zoom of the inner part of the detector. See text for details.

standing of the K^- multi-nucleon absorption reactions. No K^-pp deeply bound cluster signal was reported, while the interpretation of the data leaves open the possibility of exotic, strange tri-baryon systems.

Exclusive and possibly complete measurements of the K^- absorption events are evidently the way to go to understand the K^- absorption dynamics and possibly identify deeply bound kaonic clusters. This was the choice followed by the FINUDA experiment which studied the A(K^-, Λp) reaction at rest on sever nuclear targets. The experiment is briefly described in the following section.

3 The FINUDA experiment

The low energy (∼16MeV) K$^-$'s produced by the decay (almost) at rest of the $\phi(1020)$ at the e^+ e^- DAΦNE ϕ-factory are used by the FINUDA experiment to study kaonic interactions after absorption in thin nuclear targets. Finuda, a magnetic spectrometer with cylindrical geometry around the beams axis, uses a 1.0 T magnetic field provided by the superconducting FINUDA solenoid. In fig. 2 a sketch of the spectrometer is shown. The innermost layer, TOFINO (part of the 'interaction/target region' in fig. 2), is a segmented plastic scintillator, used for starting the spectrometer time-of-flight and discriminating kaons from electrons at a trigger level. It is followed by two layers of double-sided silicon strip detectors (ISIM and OSIM), which are used for both localizing and identifying charged particles. To the 'interaction/target region' of fig. 2 belong also the targets, placed in between ISIM and OSIM, which amount to a total thickness of a few (0.2-0.3) mg/cm^2. This gives a negligible contribution to the energy degradation of the particles exiting the target after the absorption event. Two layers of wire chambers (LMDC) surround OSIM while stereo-arranged straw tubes (ST) constitute the last sensitive layer lying inside the magnetic field. The outermost layer of FINUDA (TOFONE) consists of 72 slabs of plastic scintillator. TOFONE is designed to stop the FINUDA time-of-flight, to measure the energy released by charged particles and to act as a neutron detector. The mass identification of pions, protons, deuterons and tritons relies on the measurement of the specific energy deposit (dE/dx) in the different layers of the spectrometer. Further details about the detector and analysis techniques can be found in Refs.[19],[14] and references therein.

4 The K^-pp system

The simplest DBKN, originally forseen to bind by 48 MeV [1] and later studied by several authors [6–9] with predictions spanning over a wide range of values, is the K^-pp cluster. Such a system can be investigated via its possible decay into a (Λp) pair. The study of the Λp invariant mass distribution from the A(K^-_{stop}, Λp) reaction is therefore a natural candidate for highlighting possible K^-pp signals, although the presence of backgrounds and distortions makes it a non-trivial task. In particular, multinucleon quasi-free absorption is the main source of background in A(K^-, YN) invariant mass measurements, while collisional shift and broadening, due to FSI's of the ougoing particles, also become relevant as A increases.

4.1 The FINUDA results

The FINUDA spectrometer was designed to perform a program of high resolution hypernuclear spectroscopy studies, but thanks to its large acceptance ($> 2\pi$ sr), high momentum resolution and excellent particle mass identification it is possible to perform, with a large phase space coverage, a full topological event reconstruction of complex events. An example of an A($K^-, \pi^- pp$) event is shown in fig. 3. A $p\pi^-$ pair emerging from a secondary vertex is identified as a Λ if the value of the invariant mass of the

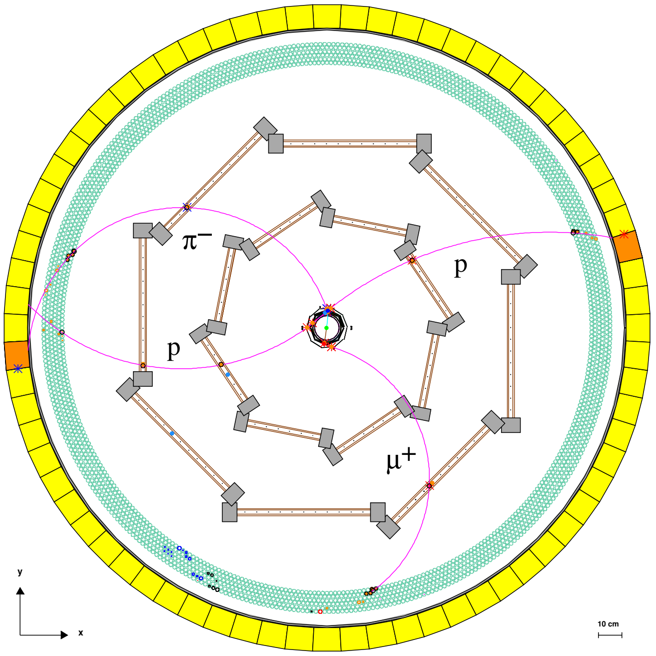

Fig. 3. Cross sectional view of the FINUDA spectrometer. A $pp\pi^-$ reconstructed event is a possible candidate for a Λp event. A μ^+ is visible from the decay of the K^+.

candidate event is in the range $1116 \pm 14 MeV/c^2$. An enhancement in the invariant mass spectrum of the Λp system was observed around 2.25 GeV/c^2 in the sum of the data collected during the first data taking period on ^{6}Li, ^{7}Li and ^{12}C targets with the Λp pairs almost back-to-back emitted [20]. A lower momentum cut at $p_\Lambda \geq 300 MeV$ was set in order to minimize the contribution of mesonic Λ production. The fact that the majority of the Λp pairs are emitted at back-to-back angles was interpreted in [20] as the indication of a 2 body decay of a system at rest. The fact that a bump appears in the Λp invariant mass spectrum at an energy much lower than the sum of one Kaon and two proton masses was taken as an indication that the emitted particles come from an intermediate K^-pp bound state and not from a direct two-nucleon absorption. Fig. 4 shows the observed peak in the Λp invariant mass spectrum with (inset) and without the acceptance correction, after applying a $\cos\Theta_{\Lambda p} \leq -0.8$ cut. The analysis assigned (2255 ± 9) MeV/c^2 to the mass of the peak. This corresponds to a binding energy B.E.= $(115^{+6}_{-5}(stat)^{+3}_{-4}(sys))$ MeV and a width $\Gamma = (67^{+14}_{-11}(stat)^{+2}_{-3}(sys))$ MeV once intepreted as a K^-pp bound state [20] .

Possile interpretations of the invariant mass bump in terms of alternative conventional effects are described in the following.

- The first hypothesis to be evaluated is that of a quasi-free $K^-_{stop}pp \to \Lambda p$ reaction, where the pp is a diproton system of the target A, leaving the residual nucleus A′in ground state. Such a reaction would be signalled by a peak at threshold (about 2.34 GeV/c^2). Such a peak can indeed be seen in the in variant mass spectrum of fig. 4 while the observed bump has a significantly lower mass.
- An interpretation of the peak was given by Magas *et al.* [21], which does not require a bound kaonic system to be formed. In their paper, which is essentially a phase space model with FSI's of the outgoing particles, but without any $\overline{K}$ absorption dynamics taken into account, the nature of the bump is explained as the combined effect of Final State Interactions (FSI) by the nucleons of the target on the particles produced after two-body kaon absorption and by $\theta_{\Lambda p}$ being constrained within a narrow phase-space ($\cos(\theta_{\Lambda p}) \leq -0.8$).
  However caution is due since, opposite to the Magas *et al.* model, the experimental Λp bump is slightly affected by the angular cut, and the back-to-back behaviour clearly shows up in the data before any cut is applied. The model was in fact shown [22] to be unable of explaining the correct shape of the Λp angular distributions, in particular the strong Λp back-to-back correlation. As a final remark, while it is obvious that, for a realistic prediction, FSI's must be included in a model describing the A($K^-, \Lambda p$) reaction, on the other side in the model of Magas *et al.* [21] FSI's on ^{12}C account for the major part of the strength of the observed Λp bump. Such an overwhelming role of FSI's appears to be excessive.
- A possible mechanism explaining the observed Λp back-to-back topology is the absorption of negative kaons leading to final $\Sigma^0 p$ pairs (mesonless production). The Σ^0 could subsequently decay into $\Lambda\gamma$ generating a signal in the Λp invariant mass at an energy which could be roughly compatible with the experimental bump. However, the relative branching fractions of the two channels is $\Lambda p/\Sigma^0 p \sim 4$ [11], which suggests that only a minor fraction of the total strength should be originated by $\Sigma^0 p$ pairs.

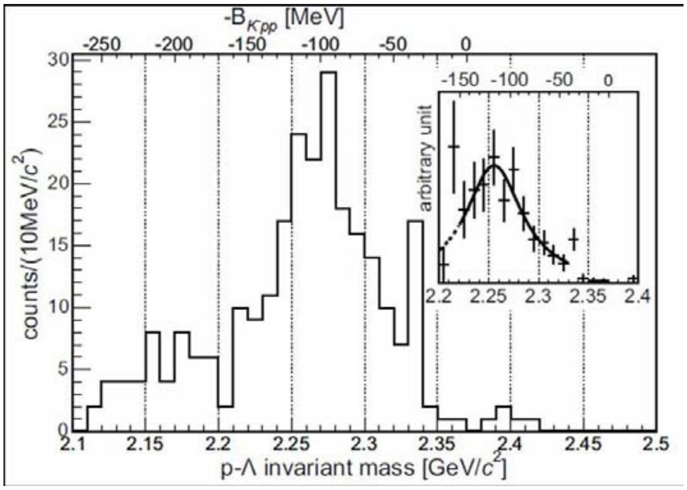

Fig. 4. (Λp) invariant mass spectrum after K^- absorption on ^{6}Li, ^{7}Li and ^{12}C targets of FINUDA [20]. The events were selected with a $\cos\Theta_{\Lambda p} \leq -0.8$ cut. In the inset the spectrum obtained after acceptance correction is shown together with a fit where a Gaussian is convoluted with a Lorentzian function. The fit was performed in the (2.22 – 2.33) GeV/c^2 interval since outside this interval the points are affected by large errors due to the large acceptance correction.

- Similar remarks about the branching ratios hold for the contributions from $K^-(pp) \rightarrow \Sigma N$ absorption on correlated nucleons of the absorbing nucleus, followed by $\Sigma N \rightarrow \Lambda p$ conversion. Moreover the additional back-to-back Λp cut should render negligible the contribution of the above reactions [21]

From the above discussion it appears clear that none of the above mentioned mechanisms is able to explain the bump nature, although some of them could indeed contribute to it.

Data from the last FINUDA runs on different targets is presently being analysed, giving some new insight on the subject, thanks also to the higher statistics collected on $^{6,7}Li,^{9} Be, D_2Oand^{13}C$ targets. A few highlights about the ongoing analysis will be given. Preliminary results for ^{6}Li indicate that the invariant mass distribution of the Λp pairs is similar in shape to the earlier published FINUDA distribution [20], except for a previously absent narrow peak at about 2220 MeV/c^2, discussed below.

Additional information on the role played by the Σ^0 production in the kaon absorption can be obtained by applying the missing mass method to the Λp pairs. As already mentioned, this method allows for a clean separation of different reaction final states.

The lighter nuclear target studied by FINUDA is the ^{6}Li, which is a reliable starting point to understand the K^- absorption processes on few nucleon systems. In addition, $\Lambda(p) - A'$ FSI's slightly affect the reaction dynamics. The preliminary analysis performed on ^{6}Li (not shown here) allows to distinguish different kinematical regions as briefly described below. At around 3750 MeV/c^2 a missing mass peak signals the contribution of the quasi-free two nucleon absorption reaction $K^-_{stop}\,{}^6\mathrm{Li} \rightarrow \Lambda p\,{}^4\mathrm{H}_{\mathrm{g.s.}}$, while the $K^-_{stop}\,{}^6\mathrm{Li} \rightarrow \Sigma^0 p\,{}^4\mathrm{H}_{\mathrm{g.s.}}$ reaction opens about 77 MeV/c^2 above. Finally, at about 3870 MeV/c^2 the $K^-_{stop}\,{}^6\mathrm{Li} \rightarrow \Lambda p\pi\,{}^4\mathrm{H}_{\mathrm{g.s.}}$ mesonic channel opens, which shows a sharp spike at threshold, probably the result of a cusp effect. This spike is correlated to the above cited 20-30 MeV/c^2 wide Λp invariant mass peak positioned at about 2220 MeV/c^2. The appearance of a sharp threshold increase is a well-known effect, already observed in the early bubble chamber experiments when studying reactions induced by kaon absorption [12]. In the past, several observations of such signals were reported, especially on deuterium targets. In the same mass region a narrow signal was recently observed by the OBELIX collaboration for the annihilation reaction $\bar{p}^4\mathrm{He} \rightarrow (p\pi^-)pK^0_S X$ [23].

The use of the missing mass spectra can therefor help in better understanding the nature of the Λp bump and role of the different mechanisms proposed to try to explain the Λp invariant mass bump. The analysis is proceeding along these lines and is expected to give a deeper insight in the understanding of the invariant mass behaviour.

A preliminary analysis of the $\Theta_{\Lambda p}$ opening angle on ^{6}Li,^{9}Be and^{16}O (see fig. 5) gives a clear indication that the Λp pairs are strongly back-to-back peaked as in the original FINUDA findings [20]. Although the spectra are not acceptance corrected, earlier studies indicate that only minor modifications are expected. It is also worth noticing that the amount of back-to-back peaking appears to be similar, regardless the nuclear target mass changing from 6 to 16. If confirmed by a more refined and quantitative analysis this would support the hypothesis that FSI's are not a major issue in interpreting the Λp invariant mass behaviour.

5 Conclusions

The existence of strongly bound $\overline{K}$ nuclear clusters has been intensively discussed in recent years. The theoretical debate, revived by Akaishi and Yamazaki [1] predictions over the existence of very deep kaonic nuclear states, is still open and has recently focussed on the prototype kaon

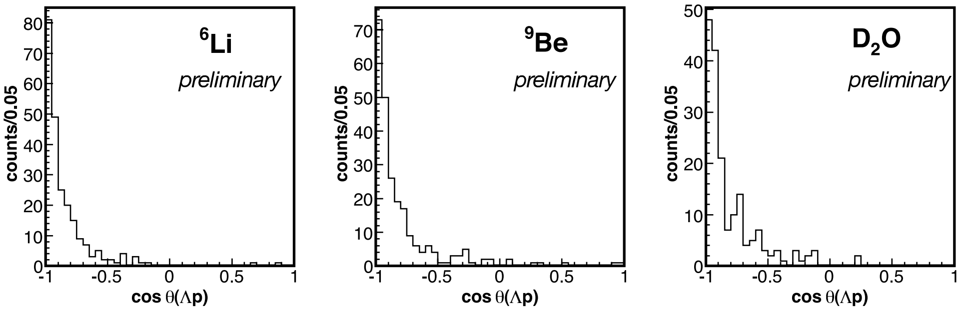

Fig. 5. Λ-proton opening angle distributions from ^{6}Li, ^{9}Be, D_2O targets. The spectra are not acceptance corrected.

nuclear system, K^-pp. The existence of a certain amount of binding is not generally questioned, but the different theoretical approaches present a variety of binding energies and widths going from a few MeV to ≥ 100 MeV. There is therefore little theoretical guidance as whether a K^-pp state exists narrow enough to be experimentally detected.

The experimental studies are still very few, and in particular only two experiments, E549 (KEK) and FINUDA (LNF) provided new results about the K^-pp system. The E549 and FINUDA experiments studied the $A(K^-, \Lambda N)$ reactions on a wide range of A: the FINUDA measurements range from A=6 up to 51 while E549 examined A=4. A reanalysis of old data of the DISTO experiment were also recently presented [24] claiming the presence of a system with a B.E.=(105+-2) MeV and Γ=118 ± 8 MeV from the study of the $pp \to K^+\Lambda p$ reaction at 2.85 GeV. Similarly, a reanalysis of $\bar{p}^4\text{He} \to (p\pi^-)pK^0_SX$ [23]assigned a mass M = 2223.2 ± 3.2stat ± 1.2syst MeV and width $\Gamma \leq 33.9\pm6.2$ MeV to a Λp invariant mass signal, with a 4.7σ statistical significance.

A lack of experimental data is one of the main reasons why the $\overline{K}N$ interaction below threshold and the nature of the $\Lambda(1405)$ are still unsettled subjects. Since these are key points in order to perform a proper treatment of the kaonic clusters this calls for an experimental effort in two directions: a direct search for deeply bound kaonic states and an improvement of the quality and statistics of the threshold $\overline{K} - N$ scattering, of the kaonic hydrogen and of the $\pi\Sigma$ mass distribution.

The task of detecting DBKN is a very challenging one: these are probably wide states and need to be disentangled from relevant backgrounds from mesonless $\overline{K}$ multinucleon absorption; moreover, if searched on heavier nuclei, the presence of collisional shift and broadening may fake or distort the signal.

The FINUDA experiment collected a total amount of ~1.2 fb^{-1} in two different data-taking periods. The experiment could fruitfully apply the invariant mass spectroscopy technique because of its capability of detecting the full DBKN decay topology. In the Λp invariant mass spectra a possible signature was found and the binding energy and the width were provided. The analysis of the FINUDA second data taking is in an advanced stage and thanks to a much higher statistics a target by target analysis will soon be obtained. It is expected that the A dependence may play a key role to understand the K^- multinucleon absorption and to disentangle the effect of FSI interactions.

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