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The $A(K^-_{stop}, \Lambda d)A'$ reaction, a tool to observe $[\overline{K}NNN]$ clusters.

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Abstract. This work presents experimental results obtained from a study of the $K^-_{stop}A \to \Lambda d A'$ reaction, where $A = {}^6Li$. The study concerns the distributions of the Λd invariant mass, which allows to determine the structure of bound $[K^-ppn]$ systems in nuclei. Such clusters are identified in the present measurement, and their masses (binding energies), decay widths and yields are reported. The experiment was performed at the DAΦNE ϕ-facility (LNF) by using the FINUDA spectrometer. The study trusted on the capability of FINUDA to reconstruct the traces of all the particles involved in the decay of the nuclear cluster.

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1 Introduction

This paper investigates the invariant mass spectra of Λd pairs, produced in the kaon absorption reaction $K^-_{stop}A \to \Lambda(1116)d\,A'$, where $A = {}^6Li$ and A' is the residual nucleus, a system of 3 nucleons not necessarily bound. The present study follows an earlier Λp survey on light and medium-light nuclei[1,2], which brought hinted that negative kaons gather nucleons of the nucleus to form bound systems; i.e., $K^-_{stop}pp \to [K^-pp] \to \Lambda p$. The present discussion is about the dynamics of $[\overline{K}NNN]$ clusters in the A nucleus, which is pursued by studying the Λd decay channel.

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2 The Data Analysis

In the FINUDA experiment negative kaons are produced by the DAΦNE collider at LNF via initial e^+e^- collisions, which originate nearly at rest $\Phi(1020)$ mesons. The prompt decay of Φ's in the $\Phi \rightarrow K^+K^-$ channel (B.R. ∼50%) is the source of the ∼16 MeV kaons, which are emitted in opposite directions. While a negative kaon initiates the reaction process, the associate positive kaon ensures the uniqueness of the K^-K^+ event. Negative kaons are slowed down to rest in solid targets; the setting choosen for the first FINUDA data taking was: 2x^6Li, 1x^7Li, 3x^{12}C, 1x^{27}Al e 1x^{51}V. The low energy of the kaons favors the use of thin tiles, i.e., as thin as 0.213 gr/cm^2 for ^6Li.
The momentum of the particles involved in the K^- absorption and decay processes, namely π's, p's and d's, is measured by the tracking system of FINUDA[3], which consists of two layers of the silicon microstrip detector, whose external layer is located at 7.5 cm from the e^+e^- crossing beams, two layers of low-mass wire chambers, and a final stack of straw tubes whose inner layer is set at 111.0 cm from the crossing beams.
The charged particles produced in the absorption (or decay) process are mass identified by their specific energy deposited (dE/dx) into some active layers of the spectrometer. In fact, a coherent response of a minimum of 3 dE/dx layers is required to identify a particle either as a pion or a proton or a deuteron. In order to check the particle discrimination contamination, the mass of the particles is independently determined by measuring their time-of-flight. The contamination in the charged particle identification turns to be less than 4%. This capability of FINUDA combined with its tracking performances allows the reconstruction of the $K^-_{stop}\,A \rightarrow \Lambda d\, A'$ reaction.
An initial K^-d vertex fixes into A the stopping point of the negative kaon. In turn, a Λ hyperon is reconstructed via the $\Lambda \rightarrow \pi^-p$ decay. These particles form a secondary vertex, which is separated from the K^-_{stop} vertex. A minimum distance (1mm) is therefore required between the two vertices. The Λd correlation is ensured since both particles belong to the same reconstructed event.

Fig. 1 depicts the $\Lambda(1116)$ invariant mass distribution when it is detected in coincidence with a deuteron and appears as a peak standing out over a small background. Such a clean discrimination of Λ is the result of the combination of a good energy resolution (Γ_Λ/m_Λ=0.8%) and of topology selection of the π^-pd events; i.e., the $\Lambda \rightarrow \pi^-p$ decays are requested to be correlated with the K^-d vertexes. In comparison with the $K^-_{stop}A \rightarrow \Lambda pA'$ reaction[1, 2], the Λ invariant mass of the $K^-_{stop}A \rightarrow \Lambda dA'$ reaction appears to be almost free from the background generated by the uncorrelated π^-p pairs.
Λ hyperons are detected from ∼140 MeV/c (threshold) up to 800 MeV/c. Deuterons from the Λd channel are analyzed starting from ∼300 MeV/c (threshold) up to momenta of about 800 MeV/c. Both Λ's and d's are measured with a resolution better than $\Delta p/p$ <2%. The wide angular acceptance of FINUDA allows for $0^\circ \leq \Theta_{\Lambda d} < 180^\circ$ Λd opening angle measurements. Finally, the spectra presented are corrected for the spectrometer acceptance, which is a source of systematic uncertainty.

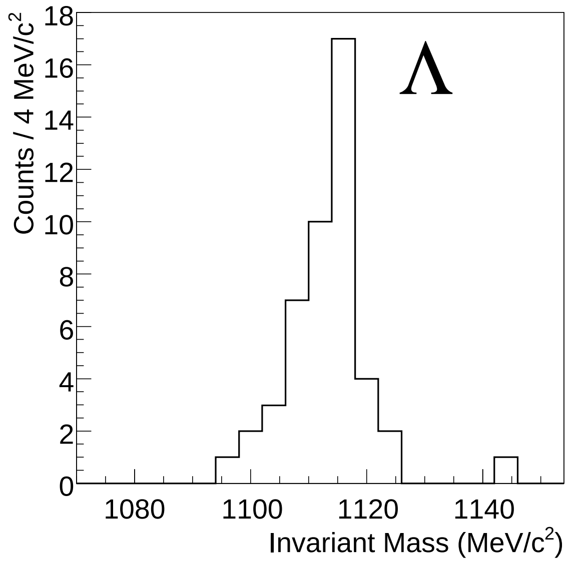

Fig. 1. Invariant mass distribution of Λ's from the $^6Li(K^-_{stop}, \Lambda d)A'$ reaction, the hyperons are identified in coincidence with deuterons.

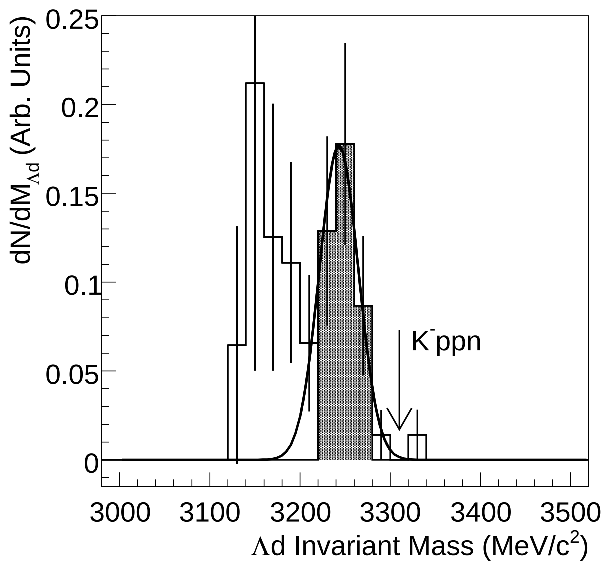

Fig. 2. Invariant mass distribution of Λd pairs from the $^6Li(K^-_{stop}, \Lambda d)A'$ reaction (open diagram). The curve is a normal fitting to the bump. The arrow indicates the overall mass of the unbound K^-ppn system.

Fig. 2 shows the Λd invariant mass ($m_{\Lambda d}$) for ^6Li, its strenght is below the overall mass of the unbound $K{-}ppn$ system, shown by an arrow in fig. 2. A broad bump at $m_{\Lambda d}$ ∼3240 MeV/c^2 emerges, whose nature has to be investigated. In order to obtain its position ($m_{\Lambda d}$), width and yield ($Y_{\Lambda d}$), the bump is fitted with a normal distribution. The measured width folds in the intrinsic width ($\Gamma_{\Lambda d}$), the bin width and the spectrometer resolution. Such

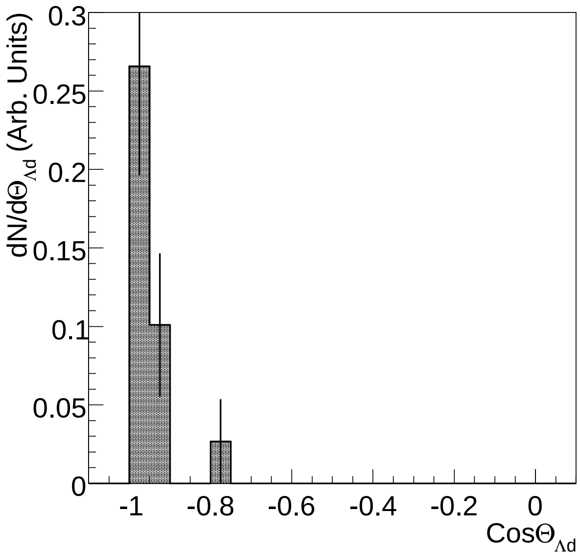

Fig. 3. Opening angle distribution of Λd pairs from ^6Li for the 3220≤ $m_{\Lambda d}$ ≤3280 MeV/c^2 events.

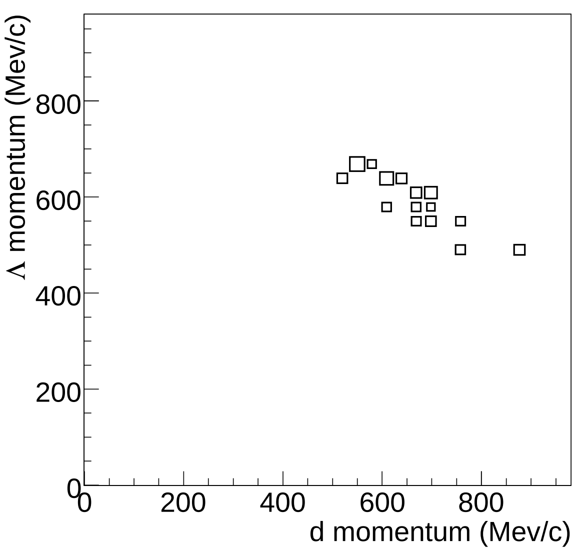

Fig. 4. Correlation between Λ and d momentum for the 3220≤ $m_{\Lambda d}$ ≤3280 MeV/c^2 events on ^6Li .

a plain fitting procedure is feasible since the bump is clearly distinct from the nearby continuum. The results are $m_{\Lambda d}$=(3243±5) MeV/c^2, $\Gamma_{\Lambda d}$=(36.8±9.7) MeV/c^2, and $Y_{\Lambda d}$=(5.4±1.4)×10^{-3}/K^-_{stop}.

Afterwards the angular distribution of the Λd pairs is studied. Fig. 3 depicts the cos$\Theta_{\Lambda d}$ distribution from ^6Li for the bump events; i.e., for events in the mass interval 3220≤ $m_{\Lambda d}$ ≤3280 MeV/c^2 (filled region of fig. 2). The distribution is peaked at cos$\Theta_{\Lambda d}$=-1. For the same events, the fig. 4 shows the Λ momentum versus the d momentum, both are centered around at 600 MeV/c. The angular and the momenta correlations suggest a typical back-to-back

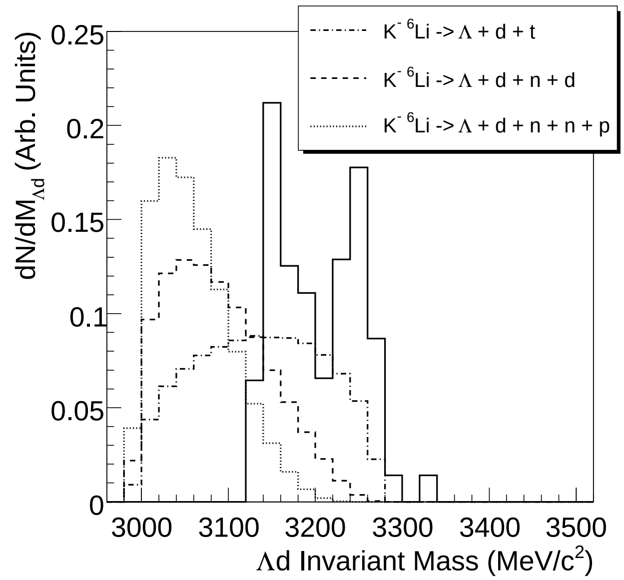

Fig. 5. Invariant mass distribution of Λd pairs from the phase space simulation of $^6Li(K^-_{stop},\Lambda d)t$ (dot-dashed histogram), $^6Li(K^-_{stop},\Lambda d)nd$ (dashed histogram) and $^6Li(K^-_{stop},\Lambda d)nnp$ (dotted histogram) reactions. The black histogram is the same of fig.2.

topology coming from a slowly moving cluster decaying into a Λd pair. As confirmation, in the bump events the Λd pair momentum spans from 50 to 350 MeV/c.

3 The Phase Space and Background Reactions

The number of baryons involved in the absorption process suggests that the negative kaon interacts with a ^3He-like substructure of ^6Li's, thus leaving an undetected $3N$ system in the reaction final state. As shown in fig. 5, if the 3N system fully breaks, the $^6Li(K^-_{stop},\Lambda d)nnp$ and the $^6Li(K^-_{stop},\Lambda d)nd$ phase spaces constrain the $m_{\Lambda d}$ distribution below 3200 and 3240 MeV/c^2 respectively; therefore, these channels can hardly contribute to form the 3243 MeV/c^2 bump.

If the undetected system remains bound, the reaction kinematics requires the kinetic energy of slowly-moving tritons to form a peak at ∼10 MeV, as shown by the dot-dashed distribution in the fig. 6. Such a peak does not appear in the missing kinetic energy spectrum (black distribution of fig. 6), which denotes that only a limited strength is available to the $^6Li(K^-_{stop},\Lambda d)t$ channel.

A previous work [4] showed that in the capture of $K-$ by ^6Li the nucleus behaves like an $\alpha + d$ system. In this analysis, $K-$ can only be absorbed by the α substructure, therefore, a fast neutron and a spectator deuteron belong to the reaction final state. Based on this assumption, the missing energy of the $^6Li(K^-_{stop},\Lambda d)nd$ reaction is the kinetic energy of the nd pairs. The distribution of

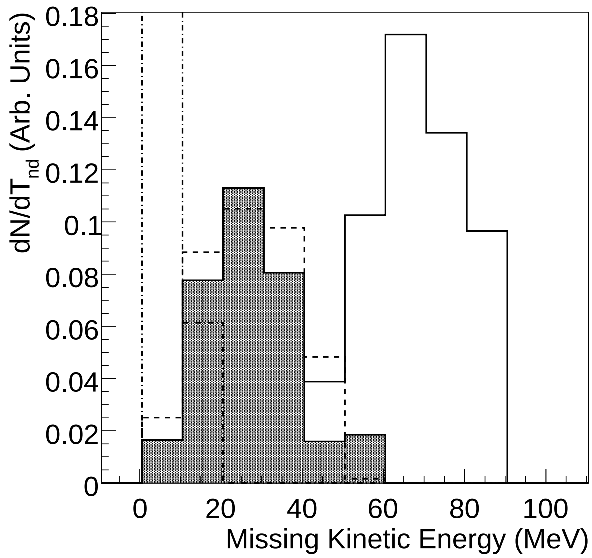

Fig. 6. Measured missing kinetic energy distribution of the $^6Li(K^-_{stop}, \Lambda d)nd$ reaction (solid histogram). Filled histogram, kinetic energy distribution of the undetected nd events correlated to the mass interval of the bump in fig. 2, namely, 3220 $\leq m_{\Lambda d} \leq$ 3280 MeV/c^2. Dashed histogram, simulated kinetic energy distribution of the undetected nd pairs with the energy of the (spectator) deuteron T_d <3 MeV. Dot-dashed histogram, simulated kinetic energy distribution of the undetected t for the $^6Li(K^-_{stop}, \Lambda d)t$ reaction.

the energy of the undetected nd pairs (T_{nd}) is reported in Fig. 6, and it is depicted up to 90 MeV since above it dN/dT_{nd} is affected by large uncertainties. The distribution presents a bump at around 25 MeV. This is found to be strongly correlated to the 3243 MeV/c^2 bump of Fig. 2; in fact, a 3220$\leq m_{\Lambda d} \leq$3280 MeV/c^2 cut produces the filled histogram of Fig. 6. This occurrence requires a careful kinematic analysis of the undetected nd pairs. To this purpose, the neutron energy distribution is simulated following the $^6Li(K^-_{stop}, \Lambda d)nd$ phase space with the deuteron constrained to be a spectator. Furthermore, the simulated distributions of Λd events are constrained to fit the measured distributions in the ranges $p_{d,\Lambda}$=600±200 MeV/c, 3220$\leq m_{\Lambda d} \leq$3280 MeV/c^2 and -1$\leq$cos$\Theta_{\Lambda d} \leq$-0.9. The result of the simulations is the dashed distribution in fig. 6, which is normalized to the experimental data. The curve follows closely the behavior of the data, pointing out that most of the kinetic energy is taken away by the undetected neutrons.

4 Conclusions

The poor statistics (25 events on the bump in ^6Li) does not affect the present results because they have been obtained by a comparison among independent observables; i.e., Λd invariant mass, momentum and opening angle and nd missing energy. In the case of ^6Li, the K^-'s are absorbed at rest by α-like substructures, $K^-_{stop}\alpha \rightarrow [K^-pd]+n$, while the remaining deuterons participate to the process as spectators. Final state neutrons remove the energy in excess. The $[K^-pd]$ clusters finally decay via the $[K^-pd] \rightarrow \Lambda d$ channel.
When $[K^-NNN]$ clusters are discussed in the framework of $\overline{K}$ bound nuclear states, the nuclear ground state of $[\overline{K}^3He]$ is predicted to be 108 MeV deep and 20 MeV wide[5]. In this framework, similar quantities can be determined by assuming that $[K^-pd]\equiv[\overline{K}\,^3He]$. The $[K^-pd]$ binding energy turns to be B_{K^-pd}=$(m_{K^-} + m_p + m_d) - m_{\Lambda d}$=64.6 ±5.3 MeV and $\Gamma_{\Lambda d}$=36.8±9.7 MeV/c^2, where m is the rest mass of a generic particle. Although the theoretical predictions agree with the experimental findings about the possibility of forming kaonic nuclear states, the quality of the agreement is poor. Further developments both on the theoretical and experimental side are needed. The present statistics does not permit to reconstruct data in the low acceptance region ($m_{\Lambda d} \leq$ 3160 MeV/c^2). This region is crucial to understand the nature of the background and to search for possible deeper bound states. As shown in Fig. 5, none of the main background reactions on ^6Li with Λd explains the 3243 MeV/c^2 bump, but they could be used to fit the lower part of the spectrum.
With the next data taking FINUDA will improve the statistical significance of the 3243 MeV/c^2 bump from 2.5σ to 7.2σ. Moreover, FINUDA will collect data in the lower acceptance region, thus allowing a significant study of the background and will be even able to reconstruct a neutron spectrum in coincidence with the Λd particles (about 30 events expected).

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