

# RECENT EXPERIMENTAL RESULTS ON THE LOW-ENERGY $K^-$ INTERACTION WITH NUCLEONS BY AMADEUS\*

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Recent results obtained by the AMADEUS Collaboration on the experimental investigation of the  $K^-$  low-energy interaction with light nuclei

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are summarised. The step 0 of AMADEUS consists in the analysis of the data collected at the DAΦNE collider with the KLOE detector during the 2004/2005 data taking campaign. The low momentum  $K^-$  particles ( $p_K \sim 127$  MeV/ $c$ ) are absorbed in the light nuclei contained in the detector setup (H,  $^4\text{He}$ ,  $^9\text{Be}$  and  $^{12}\text{C}$ ) and hyperon-pion/hyperon-nucleons, emitted in the final state, are reconstructed. From the study of  $\Lambda\pi^-$  and  $\Lambda p$  correlated production, important information on the  $\bar{K}N$  strong interaction in the non-perturbative QCD regime are extracted.

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## 1. Introduction

The AMADEUS Collaboration aims at providing experimental information on the low-energy strong interaction between  $K^-$  and nucleons with implications ranging from the domain of nuclear physics to astrophysics [1].

The investigation of the antikaon-nucleon ( $\bar{K}N$ ) interaction is fundamental for the comprehension of the nature of the  $\Lambda(1405)$  (isospin  $I = 0$ ), which means experimentally measured mass is about 27 MeV below the  $\bar{K}N$  threshold [2] and has a dynamical origin. In phenomenological potential models [3–7], the resonance is interpreted as a pure  $\bar{K}N$  bound state, in chiral models [8–12], the resonance appears as a superposition of two states coupled respectively to the  $\Sigma\pi$  and  $\bar{K}N$  channels. The relative position of the two states is determined by the strength of the  $\bar{K}N$  interaction potential. The experimental investigation of the  $\Lambda(1405)$  properties is also challenging because the resonance line-shape is found to depend on both the production mechanism and the observed decay channel. Moreover, if the  $\Lambda(1405)$  is produced in  $K^-$ -induced reactions, the non-resonant  $\Sigma\pi$  production contribution has to be considered. In Ref. [13], the non-resonant hyperon-pion ( $Y\pi$ ) production in the  $I = 1$  channel, where the resonant counterpart due to the  $\Sigma(1385)$  formation is well-known, is investigated. In Section 2, the results obtained in Ref. [13] are summarised.

The strength of the  $\bar{K}N$  sub-threshold interaction also influences the formation of bound states of antikaons with more than one nucleon. The experimental search of such exotic bound states in  $K^-$ -induced reactions cannot disregard a comprehensive characterisation of the  $K^-$  multi-nucleon absorption processes due to the overlap with the  $K^-$  bound state formation over a broad range of the phase space [14, 15]. The  $K^-$  multi-nucleon absorption cross sections at low-energy are also crucial for the interpretation of the data in heavy-ion collisions [16]. The role of the  $K^-$  absorption on more than one nucleon has been recently demonstrated to be fundamental in the determination of the  $K^-$ -nucleus optical potential [17, 18]. A phenomenological  $K^-$  multi-nucleon absorption term, constrained by global absorption

bubble chamber data, was added to the  $K^-$  single-nucleon potential, in order to achieve good fits to  $K^-$  atoms data along the periodic table [17, 18]. In Ref. [19], a complete study of the  $K^-$  interactions with two, three and four nucleons ( $2NA$ ,  $3NA$  and  $4NA$ ) processes has been performed. The details of the data analysis will be given in Section 3.

The step 0 of AMADEUS consists in the re-analysis of the data collected by the KLOE Collaboration [20] during the 2004/2005 data taking campaign and corresponding to  $1.74 \text{ fb}^{-1}$  integrated luminosity. The low-momentum  $K^-$  ( $p_K \sim 127 \text{ MeV}/c$ ), produced at the DAΦNE collider [21] from the  $\phi$ -meson decay nearly at-rest, are captured on the nuclei in the materials of the beam pipe setup and of the KLOE detector (H,  $^4\text{He}$ ,  $^9\text{Be}$  and  $^{12}\text{C}$ ) used as active target. The analysed data sample allows to investigate both at-rest ( $p_K \sim 0 \text{ MeV}/c$ ) and in-flight  $K^-$  nuclear captures.  $Y\pi$  and  $YN$ /nuclei pairs produced in the final state of the  $K^-$  absorptions are reconstructed.

## 2. Modulus of the $K^-n \rightarrow \Lambda\pi^-$ amplitude below threshold

The experimental investigation of the  $\Lambda(1405)$  properties, produced in stopped  $K^-$  reactions with light nuclei, is disturbed by two main biases:

- the  $\Sigma\pi$  ( $I = 0$ ) invariant mass line-shape is biased by the energy threshold, shifted from 1432 MeV to lower energies (1412 MeV in  $^4\text{He}$  and 1416 MeV in  $^{12}\text{C}$ ) due to the separation energy of the absorbing proton. In in-flight  $K^-$  reactions, the energy threshold is shifted upward due to the kinetic energy of the kaon'
- the shape of the non-resonant  $K^-p \rightarrow (\Sigma\pi)^0$  reactions has to be taken into account.

In Ref. [13], the non-resonant  $K^-n \rightarrow \Lambda\pi^-$  process is investigated, considering  $K^-n$  single-nucleon absorptions on  $^4\text{He}$ . Since the  $\Sigma^-(1385)$  ( $I = 1$ ) resonance is well-known, the corresponding non-resonant transition amplitude ( $|T_{K^-n \rightarrow \Lambda\pi^-}|$ ) can be extracted and used to test the theoretical predictions below threshold.

In this work, the experimentally extracted  $\Lambda\pi^-$  invariant mass, momentum, and angular distributions were simultaneously fitted by using dedicated MC simulations. All the contributing reactions were taken into account: non-resonant processes, resonant processes and the primary production of  $\Sigma$  followed by the  $\Sigma N \rightarrow \Lambda N'$  conversion process. The simulations of non-resonant/resonant processes were based on the results of [22]. The analysis allowed the extraction of the non-resonant transition amplitude modulus  $|T_{K^-n \rightarrow \Lambda\pi^-}|$  at  $\sqrt{s} = (33 \pm 6) \text{ MeV}$  below the  $\bar{K}N$  threshold, which is found to be

$$|T_{K^-n \rightarrow \Lambda\pi^-}| = \left( 0.334 \pm 0.018 \text{ (stat.)}_{-0.058}^{+0.034} \text{ (syst.)} \right) \text{ fm}. \quad (1)$$

The result of this analysis (with combined statistical and systematic errors) is shown in Fig. 1 and compared with the theoretical predictions (see Refs.: Ramos–Magas–Feijoo [23], Ikeda–Hyodo–Weise [24], Cieplý–Smejkal [25], Guo–Oller 1 and 2 [26], Mai–Meissner 2 and 4 [27]). This measurement can be used to test and constrain the S-wave  $K^-n \rightarrow \Lambda\pi^-$  transition amplitude calculations.

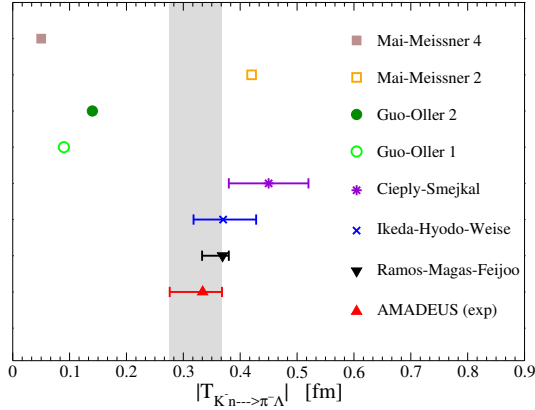


Fig. 1. Modulus of the non-resonant amplitude for the  $K^-n \rightarrow \Lambda\pi^-$  process at 33 MeV below the  $\bar{K}N$  threshold obtained by AMADEUS, compared with theoretical predictions: Ramos–Magas–Feijoo [23], Ikeda–Hyodo–Weise [24], Cieplý–Smejkal [25], Guo–Oller 1 and 2 [26], Mai–Meissner 2 and 4 [27]. The plot was adapted from Ref. [28].

### 3. $K^-$ multi-nucleon absorption branching ratios and cross sections

The absorption of the  $K^-$  on two, three or more nucleons is investigated by the AMADEUS Collaboration in Refs. [15, 19], by reconstructing  $\Lambda p$  and  $\Sigma^0 p$  pairs emitted in  $K^-$  hadronic interactions with  $^{12}\text{C}$  nuclei.

In Ref. [19], Branching Ratios (BRs) and cross sections of the  $K^-$   $2NA$ ,  $3NA$  and  $4NA$  were obtained by means of a simultaneous fit of the  $\Lambda p$  invariant mass,  $\Lambda p$  angular correlation,  $\Lambda$  and proton momenta using the simulated distributions for both direct  $\Lambda$  production and  $\Sigma^0$  production followed by  $\Sigma^0 \rightarrow \Lambda\gamma$  decay. The  $K^-$  nuclear capture was calculated for both at-rest and in-flight interactions, based on the  $K^-$  absorption model described in Refs. [22, 29]. In the first case, the absorption from atomic  $2p$  state is assumed. Fragmentations of the residual nucleus following the hadronic interaction were also considered. For the  $2NA$ , the important contributions of both final-state interactions (FSI) of the  $\Lambda$  and the proton were taken

into account, as well as the conversion of primary produced sigma particles ( $\Sigma N \rightarrow \Lambda N'$ ); this allows to disentangle the quasi-free (QF) production. The global BR for the  $K^-$  multi-nucleon absorption in  $^{12}\text{C}$  (with  $\Lambda(\Sigma^0)p$  final states) is found to be compatible with bubble chamber results. The measured BRs and low-energy cross sections of the distinct  $K^- 2NA$ ,  $3NA$  and  $4NA$ , reported in Table I, will be useful for the improvement of microscopical models of the  $K^- NN$  absorption and for a future generalisation to  $K^-$  absorption reaction calculations involving even more than two nucleons.

TABLE I

Branching ratios (for the  $K^-$  absorbed at-rest) and cross sections (for the  $K^-$  absorbed in-flight) of the  $K^-$  multi-nucleon absorption processes. The  $K^-$  momentum is evaluated in the centre-of-mass reference frame of the absorbing nucleons, thus it differs for the  $2NA$  and  $3NA$  processes. The statistical and systematic errors are also given.

Process	Branching ratio [%]	$\sigma$ [mb]	@ $p_K$ [MeV/c]
$2NA\text{-QF } \Lambda p$	$0.25 \pm 0.02(\text{stat.})^{+0.01}_{-0.02}(\text{syst.})$	$2.8 \pm 0.3(\text{stat.})^{+0.1}_{-0.2}(\text{syst.})$	@ 128 $\pm$ 29
$2NA\text{-FSI } \Lambda p$	$6.2 \pm 1.4(\text{stat.})^{+0.5}_{-0.6}(\text{syst.})$	$69 \pm 15(\text{stat.}) \pm 6(\text{syst.})$	@ 128 $\pm$ 29
$2NA\text{-QF } \Sigma^0 p$	$0.35 \pm 0.09(\text{stat.})^{+0.13}_{-0.06}(\text{syst.})$	$3.9 \pm 1.0(\text{stat.})^{+1.4}_{-0.7}(\text{syst.})$	@ 128 $\pm$ 29
$2NA\text{-FSI } \Sigma^0 p$	$7.2 \pm 2.2(\text{stat.})^{+4.2}_{-5.4}(\text{syst.})$	$80 \pm 25(\text{stat.})^{+46}_{-60}(\text{syst.})$	@ 128 $\pm$ 29
$2NA\text{-CONV } \Sigma/\Lambda$	$2.1 \pm 1.2(\text{stat.})^{+0.9}_{-0.5}(\text{syst.})$	—	—
$3NA \Lambda pn$	$1.4 \pm 0.2(\text{stat.})^{+0.1}_{-0.2}(\text{syst.})$	$15 \pm 2(\text{stat.}) \pm 2(\text{syst.})$	@ 117 $\pm$ 23
$3NA \Sigma^0 pn$	$3.7 \pm 0.4(\text{stat.})^{+0.2}_{-0.4}(\text{syst.})$	$41 \pm 4(\text{stat.})^{+2}_{-5}(\text{syst.})$	@ 117 $\pm$ 23
$4NA \Lambda pnn$	$0.13 \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$	—	—
Global $\Lambda(\Sigma^0)p$	$21 \pm 3(\text{stat.})^{+5}_{-6}(\text{syst.})$	—	—

The  $\Lambda p$  direct production in  $2NA\text{-QF}$  is phase space favoured with respect to the corresponding  $\Sigma^0 p$  final state, the ratio between the final-state phase spaces for the two processes is  $\mathcal{R}' \simeq 1.22$ . From the BRs in Table I, we measure

$$\mathcal{R} = \frac{\text{BR}(K^- pp \rightarrow \Lambda p)}{\text{BR}(K^- pp \rightarrow \Sigma^0 p)} = 0.7 \pm 0.2(\text{stat.})^{+0.2}_{-0.3}(\text{syst.}). \quad (2)$$

The dominance of the  $\Sigma^0 p$  channel is then evidence of the important dynamical effects involved in the measured processes; hence the ratio in Eq. (2) gives important information on the  $\bar{K}N$  dynamics below the threshold [30].

The possible contribution of a  $K^-pp$  bound state, decaying into a  $\Lambda p$  pair, was also investigated. The  $2NA$ -QF is found to completely overlap with the  $K^-pp$ , except for small, unphysical, values of the bound state width of the order of 15 MeV/ $c^2$  or less. A further selection of back-to-back  $\Lambda p$  production was performed by selecting  $\cos\theta_{\Lambda p} < -0.8$  in order to make a direct comparison with the corresponding FINUDA measurement. The invariant-mass distribution is compatible with the shape presented in Ref. [31]. The obtained spectra are completely described in terms of  $K^-$  multi-nucleon absorption processes, with no need of a  $K^-pp$  component in the fit, and the extracted BRs are in agreement with those obtained from the fit of the full data sample.

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