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}He, ^{9}Be and ^{12}C) and hyperon–pion/hyperon–nucleons, emitted in the final state, are reconstructed. From the study of $\Lambda\pi^-$ and Λp 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 fb^{-1} integrated luminosity. The low-momentum K^- ($p_K \sim 127$ MeV$/c$), produced at the DAΦNE collider [21] from the ϕ-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}He, ^{9}Be and ^{12}C) used as active target. The analysed data sample allows to investigate both at-rest ($p_K \sim 0$ 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 $K^-n \to \Lambda\pi^-$ 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}He and 1416 MeV in ^{12}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 $K^-p \to (\Sigma\pi)^0$ reactions has to be taken into account.

In Ref. [13], the non-resonant $K^-n \to \Lambda\pi^-$ process is investigated, considering K^-n single-nucleon absorptions on ^{4}He. Since the $\Sigma^-(1385)$ ($I = 1$) resonance is well-known, the corresponding non-resonant transition amplitude ($|T_{K^-n\to\Lambda\pi^-}|$) 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 Σ followed by the $\Sigma N \to \Lambda N'$ 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 $|T_{K^-n\to\Lambda\pi^-}|$ at $\sqrt{s} = (33 \pm 6)$ MeV below the $\bar{K}N$ threshold, which is found to be

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

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 $K^- n \to \Lambda\pi^-$ transition amplitude calculations.

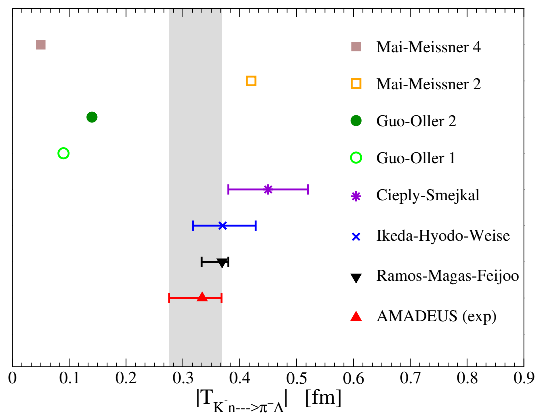

Fig. 1. Modulus of the non-resonant amplitude for the $K^- n \to \Lambda\pi^-$ process at 33 MeV below the $\bar{K}N$ threshold obtained by AMADEUS, compared with theoretical predictions: Ramos–Magas–Feijoo [23], Ikeda–Hyodo–Weise [24], Cieplý–Smejkal [25], Guo–Oller 1 and 2 [26], Mai–Meissner 2 and 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 Λp and $\Sigma^0 p$ pairs emitted in K^- hadronic interactions with ^{12}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 Λp invariant mass, Λp angular correlation, Λ and proton momenta using the simulated distributions for both direct Λ production and Σ^0 production followed by $\Sigma^0 \to \Lambda\gamma$ 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 Λ and the proton were taken into account, as well as the conversion of primary produced sigma particles ($\Sigma N \to \Lambda N'$); this allows to disentangle the quasi-free (QF) production. The global BR for the K^- multi-nucleon absorption in ^{12}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 [%]	σ [mb]	@	p_K [MeV/c]
$2NA$-QF Λp	$0.25\pm0.02(\text{stat.})^{+0.01}_{-0.02}(\text{syst.})$	$2.8\pm0.3(\text{stat.})^{+0.1}_{-0.2}(\text{syst.})$	@	128 ± 29
$2NA$-FSI Λp	$6.2\pm1.4(\text{stat.})^{+0.5}_{-0.6}(\text{syst.})$	$69\pm15(\text{stat.})\pm6(\text{syst.})$	@	128 ± 29
$2NA$-QF $\Sigma^0 p$	$0.35\pm0.09(\text{stat.})^{+0.13}_{-0.06}(\text{syst.})$	$3.9\pm1.0(\text{stat.})^{+1.4}_{-0.7}(\text{syst.})$	@	128 ± 29
$2NA$-FSI $\Sigma^0 p$	$7.2\pm2.2(\text{stat.})^{+4.2}_{-5.4}(\text{syst.})$	$80\pm25(\text{stat.})^{+46}_{-60}(\text{syst.})$	@	128 ± 29
$2NA$-CONV Σ/Λ	$2.1\pm1.2(\text{stat.})^{+0.9}_{-0.5}(\text{syst.})$	—		—
$3NA$ Λpn	$1.4\pm0.2(\text{stat.})^{+0.1}_{-0.2}(\text{syst.})$	$15\pm2(\text{stat.})\pm2(\text{syst.})$	@	117 ± 23
$3NA$ $\Sigma^0 pn$	$3.7\pm0.4(\text{stat.})^{+0.2}_{-0.4}(\text{syst.})$	$41\pm4(\text{stat.})^{+2}_{-5}(\text{syst.})$	@	117 ± 23
$4NA$ Λpnn	$0.13\pm0.09(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$	—		—
Global $\Lambda\,(\Sigma^0)\,p$	$21\pm3(\text{stat.})^{+5}_{-6}(\text{syst.})$	—		—

The Λp direct production in $2NA$-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

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

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 Λp 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 Λp 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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